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# Introduction

The European Union has set itself a binding target of achieving climate neutrality by 2050, with an intermediate ambition of reducing emission by 55% by 2030 compared to 1990 levels. European and national legislation aimed at achieving these targets have led to a notable increase in decentralised renewable energy sources, such as wind and solar PV, as well as an accelerated electrification of the mobility sector. The intermittent nature of decentralised electricity production and the hike in electricity consumption have led to new challenges with regard to grid reliability: supply and demand has become increasingly difficult to balance and the electronic power quality has become more challenging to manage effectively [1][2].

Electric vehicle (EV) charging can prove to be part of the solution to these problems through the use of smart charging, the essence of which is to change the time, speed and/or direction of the charging process. An emerging application of smart charging is vehicle-to-grid (V2G), in which energy from EV batteries can be used to feed electricity back into the grid as a way to avert grid congestion and to help match supply and demand. The scale-up to mass market V2G usage necessitates that EVs and charging stations are V2G ready: soft- and hardware modifications are necessary to support the latest technologies, ensure compliance with national grid codes, and facilitate reliable and cyber secure communication via the use of communication protocols.

The overall goal of this report is to provide an overview of the legislatorial acts and standards relevant for V2G in the European market, with an emphasis on four frontrunners of V2G: Germany, France, the Netherlands, and Sweden. These countries are the EU Member States with respectively the highest total number of charging stations (Germany, France, the Netherlands) and the highest market share of EVs (the Netherlands, Sweden). Furthermore, this report will review the American grid code requirements as a point of reference.

This document is divided into five sections. The first section specifies the scope of this report and encompasses an overview of the regulations and standards relevant for the European and American cases. The second section provides an overview of technical requirements related to the system security of the interconnected transmission system. Third, the additional requirements related to the operation of distributed energy resources relevant to the distribution system management are discussed. The fourth section examines specific deliberations relevant to e-mobility that were not yet discussed in the previous sections. Finally, this report concludes with a set of recommendations based on the analysis.

# Scope

## Requirements for Generators

Devices connected to the electricity grid have an effect on grid aspects such as frequency and voltage, and thus may jeopardise the system security as a whole. A deviation from the nominal voltage and frequency levels can lead to energy losses and damage to electronic components. Therefore, it is important to establish a set of requirements all equipment connected to the grid need to comply with, in order to ensure the stable operation of the grid with a growing share of intermittent renewable energy generation. In 2016, the European Network of Transmission System Operators for Electricity (ENTSO-E) published a series of legislatorial acts, which includes regulations establishing network codes on demand connection (DCC, 2016/1388) and on requirements for grid connection of generators (RfG, 2016/631).

Although V2G does not simply operate in consumption or generation mode, but as a combination of the two (storage), it should be noted that the DCC and RfG codes still apply. Energy storage is a novel addition to European law, defined in the revised Electricity Market Directive (2019/944) as an activity separate from generation and consumption [5]. It was therefore initially unknown whether the DCC and RfG codes should be applied to storage units. The European Union Agency for the Cooperation of Energy Regulators (ACER) states in a policy paper on the revision of the RfG that “storage units principally operate in injection and withdrawal modes, and hence, rules for power-generator facilities and demand facilities shall apply accordingly.” The regulatory authorities in the Netherlands (ACM) and Germany (BNetzA) also argue that storage units should comply with both the DCC and RfG [6][7][8]. The scope of this report is limited to requirements for V2G specifically. The DCC, which is applicable to both normal and V2G ready charging stations, will therefore not be elaborated on further.

Most requirements in the RfG are non-exhaustive. This means that the code determines allowable parameters and Member States can freely select within the given range. As a result, there are some significant differences in the national implementation of the RfG between Member States, which can have an impact on the mass market production of electricity generation units. The differences in RfG implementation between the four selected Member States are further explored in the third chapter. A key distinction between Member States lies at the distinction between different generation units. The RfG divides generation units, also known as power-generating modules (PGMs) in four categories (Type A – D). The category a PGM falls under is based on the voltage level at the connection point and the maximum power in kW. Member States can decide the thresholds of the maximum power for each category. This is important in the context of e-mobility because the obligatory requirements for Type B PGMs are much more stringent than Type A requirements. Consequently, EV and charging station manufacturers have to deal with a different set of technical requirements for each Member State they want to sell their product in, which is a crucial barrier for mass scale production of V2G-ready infrastructure. Below is an overview of the thresholds for Type A and Type B PGMs in the selected Member States.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Germany | France | The Netherlands | Sweden |
| Type A | 0,8 kW – 135 kW | 0,8 kW – 1 MW | 0,8 kW – 1 MW | 0,8 kW – 1,5 MW |
| Type B | 135 kW – 36 MW | 1 MW – 18 MW | 1 MW – 50 MW | 1,5 MW – 10 MW |

Table 1: Type A and B thresholds [9]

Within the context of V2G, both Type A and Type B might be relevant. The threshold between Type A and Type B is set as low as 10 (Slovenia) or 11 (Italy) kW in some Member States, which means that most V2G capable charging stations have to comply with Type B requirements in these countries. Furthermore, it is expected that higher charging power will be available in the near future. The Megawatt Charging System will support a power of hundreds of kW and will likely include V2G capabilities. Similarly, from the system operator point of view, a large number of charging stations connected synchronously at one connection point (for example at a depot), might be considered as a single PGM and are thus also subject to Type B requirements. However, this report will only look at the specifications for Type A PGMs and the implementation of the RfG in the selected countries.

Another important distinction in national implementation is the fact that – while there are a set of mandatory requirements for Type A requirements applicable to all V2G purposes regardless of maximum power – Member States can decide to impose additional requirements to Type A PGMs. Most notably, the German grid connection code VDE-AR-N 4105 specifies requirements for all PGMs connected to the low voltage grid, which also includes all Type B requirements of the RfG and a number of provisions relevant for distribution grid management. These requirements are illustrated in more detail in the third and fourth chapters.

## Technical standards

The European standardisation agency CENELEC published the standards EN 50549-1 and EN 50549-2 as a means to improve compatibility between national grid codes. The standards define specific parameters based on the RfG requirements for Type A and B PGMs. Furthermore, the standards also include requirements for distribution grid management, which are not covered in the RfG or only covered for Type C and D PGMs. Within the scope of this report only EN 50549-1 will be considered, which is aimed at connection requirements for PGMs connected to the low voltage grid. This standard functions as a guidance document for the RfG, but is not an European legislatorial act itself. National transposition is therefore not mandatory.

Aspects regarding the impact of grid connected electronic equipment on power quality and local voltage increase are excluded from the scope of the RfG and are likewise not included in EN 50549-1. Power quality requirements need to be taken into account as electronic equipment need to be resilient to disturbances caused by voltage deviations, frequency deviations, and harmonics. Requirements on power quality are specified in the European standard EN 50160 and the IEC 61000 series.

IEEE Standard 1547-2018 will also be analysed as a point of reference. The standard focuses on the grid connection requirements for distributed energy resources in the American market, which likely includes V2G EVs and charging stations. IEEE 1547-2018 is currently implemented by fifteen US states, including California and New York. The remaining states are expected to implement the standard in the following years. Currently, the older version IEEE 1547-2003 is in use in these states.

# Transmission system aspects

This chapter provides an overview of the technical requirements for PGMs related to the interconnected transmission grid. First, the necessary requirements for all Type A PGMs are discussed in sections 3.1 to 3.3. Miscellaneous requirements related to transmission system aspects that are mentioned in EN 50549-1 and implemented in at least one of the four selected Member States are discussed in section 3.4. The full list of requirements – both related to the transmission and the distribution grid – are displayed in table 2.

|  |  |  |  |
| --- | --- | --- | --- |
| **Requirement** | **RfG: Type A** | **EN 50549-1** | **IEEE 1547-2018** |
| **Transmission system aspects** | | | |
| *Emergency state – over- and underfrequency* | | | |
| Limited frequency sensitive mode – overfrequency | Included | Included | Included |
| Limited frequency sensitive mode - underfrequency | Included for storage facilities | Included for storage facilities | Included |
| Logic interface to cease active power | Included | Included | *TBD* |
| *Continued operation* | | | |
| Frequency ranges and minimum time periods for operation | Included | Included | Included |
| Admissible active power reduction with falling frequency | Included | Included | Included |
| Resistance to frequency gradients | Included | Included | Included |
| *Automatic connection to the network* | | | |
| Required frequency and voltage ranges | Included | Included | Included |
| *Miscellaneous* | | | |
| Frequency related protection |  | Included | Included |
| Undervoltage ride through |  | Included | Included |
| Overvoltage ride through |  | Included | Included |
| Post fault reconnection requirements |  | Included (Type B only) | Included |
| Post fault active power recovery |  | Included | *TBD* |
| **Distribution system aspects** | | | |
| Anti-islanding |  | Included | Included |
| Voltage related active power reduction |  | Included | Included |
| Voltage ranges and minimum time periods for operation |  |  | Included |
| Voltage related protection |  | Included | Included |
| Reactive power capabilities |  | Included | Included |
| Reactive power control |  | Included | Included |
| **Power Quality** | | | |
| Power quality requirements | Power quality requirements are outside the scope of RfG/50549-1. PQ requirements are described in standards EN 50160 and the IEC 61000 series. | | Included |

Table 2: overview of grid connection requirements for PGMs

## Emergency state – over- and underfrequency

Member states are required to design a system defence and restoration plan in accordance with the European network code on electricity emergency and restoration (ER code) [10]. The transmission system shall be considered to be in the emergency state depending on notable fluctuations in frequency levels, voltage levels, a system split, and other factors [11]. If the emergency state is the result of frequency fluctuations, Type A storage units should regulate their active power output in accordance with frequency levels. An emergency state as the result of other factors does not require support functions of small size storage units or PGMs, such as EVs and charging stations. When the frequency falls outside the range of 49,8 – 50,2 Hz in Germany, France, and the Netherlands, the transmission system shall be declared to be in an emergency state, and the limited frequency sensitive modes shall be activated. In Sweden, an emergency state based on frequency deviations is only declared when the frequency falls outside the range of 49,5 – 50,5 Hz.

### Limited frequency sensitive mode – overfrequency (LFSM-O)

When the system is in a state of emergency as a result of overfrequency (50,2 Hz in Continental Europe; 50,5 Hz in Nordic Europe) and this state cannot be mitigated by primary reserves (FCR) only, LFSM-O is to be activated. This requirement is elaborated upon in the RfG (article 13(2)) and EN 50549-1. Storage units operating in generation mode are required to reduce their active power output linearly according to a droop set between 2% and 12%Hz. A 5% droop setting means that if the frequency increases by 5% compared to the nominal value, the PGMs power output should decrease by 100%. Similarly, a frequency spike of 1% leads to a minimum 20% decrease in power output. Below is an overview of the default frequency thresholds at which LFSM-O and the default droop setting at activation of LFSM-O [12].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Frequency threshold | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,5 Hz |
| Droop % | 2% to 12%  Default: 5% | 3% to 12%  Default: 5% | 4% to 12%  Default: 5% | 8% |
| Further actions | Further reduction in active power | N/A | Operation to continue | Operation to continue |
| Sources | VDE AR N 4105: 2018-11;  Paragraph 5.7.4.2.3 | Arrêté du 9 juin 2020;  Article 37 | Netcode elektriciteit;  Article 3.13 (4) | Föreskrift EIFS 2018:2;  Chapter 3(3) – 3(6) |

Table 3: LFSM-O requirements in selected countries.

Based on the default frequency thresholds and droop setting, the mandatory decrease in active power output for different rising frequency levels can be calculated. Table 4 (see appendix) gives an overview of the mandatory decrease in active power output at increasing frequency rates.

LFSM-O is an important requirement to deal with the 50,2 Hz problem. Prior to the implementation of this requirement, PGMs were required to shut down completely when the grid frequency exceeded 50,2 Hz. With the increase of solar PV, the simultaneous shutdown of PGMs would only further destabilize the frequency, because a large percentage of generation would be lost immediately. With LFSM-O in place, PGMs only need to lower their active power output slightly starting at an overfrequency of 200 mHz and are only required to shut off completely when the grid frequency reaches 51,5 Hz or higher.

### Limited frequency sensitive mode – underfrequency (LFSM-U)

According to the ER code, all storage units acting as a load should switch to generation mode when the system is in a state of emergency as a result of underfrequency [10]. LFSM-U is only mentioned in the RfG for Type C and D PGMs, but should also be applied to storage units according to the ER code. EN 50549-1 mentions LFSM-U as a requirement for all storage units. Member States should set the frequency threshold between 46,0 Hz and 49,8 Hz with a droop setting between 2% and 12%Hz.

LFSM-U is still a point of contention in multiple Member States. The Netherlands agreed on LFSM-U for storage units, but did not yet implement this in the national grid code and the specified droop of 1%Hz in the national system defence plan deviates from the European standard. In France, the requirement is not mentioned in the system defence plan – and as an extension neither in the national grid code – as there was not yet an European definition on energy storage at the time of implementation of the European network code [13]. In Sweden, the implementation of the system defence plan has been delayed and is expected to be released in 2023 [14].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Applicable to | Storage units in standby mode and charging mode |  | Storage units in standby mode. |  |
| Frequency threshold | 49.8 Hz | N/A | 49.8 Hz | N/A |
| Droop % | 2% |  | 1% |  |
| Disconnection from grid | Immediately at 47.5 Hz. |  | Immediately at 47.5 Hz.  Within 10s at 49.7 Hz and immediately at 49.3 Hz if storage unit is not capable of moving to generation mode autonomously. |  |
| Sources | VDE AR N 4105:  2018-11;  Paragraph 5.7.4.2.3  VDE-AR-N 4142 |  | Tennet: Systeembeschermings- en herstelplan, p. 28  Will be implemented in the Dutch grid code in late 2022. Article 2.16(3)(f) |  |

Table 5: LFSM-U requirements in selected countries.

Starting at 49.8 Hz, storage units in storage mode or consumption mode should decrease their active power output and switch to generation mode based on a droop setting of 1%/2%. Based on the set frequency thresholds and droop setting, the mandatory decrease and increase in active power output for different dropping frequency levels can be calculated. Table 6 (see appendix) gives an overview of the mandatory variation in active power output at decreasing frequency rates.

The American standard IEEE 1547-2018 specifies frequency droop settings for both under- and overfrequency. A PGM should respond to abnormal frequencies by changing its active power output based on droop formulas defined in IEEE 1547-2018.

### Logic interface to cease active power output

According to RfG article 13(6): “the power-generating module shall be equipped with a logic interface (input port) in order to cease active power output within five seconds following an instruction being received at the input port.” The interface enables the PGM to receive a signal or set point from the relevant system operator and completely cease active power. A comparable interface is required for Type B PGMs, but rather than simply ceasing active power after receiving a signal, active power should be reduced in incremental steps. This allows for a more flexible active power adjustment than the simple binary response for Type A PGMs. The final report from the Expert Group “Baseline for Type A Power Generating Modules” recommends extending the more flexible active power controllability to Type A PGMs as well [15].Though active power control is mentioned specifically in relation to frequency stability in the RfG, it should be noted that system operators could also benefit from the interface as a fallback mechanism, for example when market based congestion management mechanisms fail to adequately deal with grid congestion.

The binary logical interface requirement is mentioned in German, French and Dutch grid codes, but no direct specifications are given on how a PGM should receive signals and instructions from a system operator. System operators can request additional equipment to make remote operation of the interface possible, but currently opt to not demand this due to increased costs for consumers and potentially decreased energy efficiency [15]. In The Netherlands, grid operators mainly focused their research on interfaces for Type B PGMs, as their higher capacities and more flexible control options will have a more notable impact on frequency stability than the binary Type A approach [16]. In France, network operators do not intend to make remote control mandatory for Type A PGMs either [17].

## Continued Operation

TSOs are responsible for restoring the grid frequency to safe levels during periods of system disturbance. If PGMs would trip as a result of such frequency disturbances, additional generation would be lost, which would further exacerbate the system instability. All PGMs must therefore remain connected to the grid at specified frequency and rate of change of frequency (RoCoF) levels. Simultaneously, PGMs should decrease their active power output during periods of overfrequency (LFSM-O) and, if possible, should switch from consumption to generation mode during periods of underfrequency (LFSM-U).

### Frequency ranges and minimum time periods for operation

Minimum time periods for operation is an important measure to ensure frequency stability. In short, PGMs need to be able of operating on different frequencies without disconnecting from the network. Preventing the loss of generation for at least 30 minutes will ensure that TSOs have enough time to activate reserve capacity and restore the grid frequency to its normal range. Longer time periods are undesirable from the manufacturer’s perspective as continuing to operate during large frequency deviations can lead to damage to electronic equipment.

The RfG (Art. 13(1)) and EN 50549-1 define different parameters for Continental and Nordic Europe regarding minimum time periods for operation. Despite these different parameters, the minimum time periods for operation are consistent throughout the researched countries.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency range | **Germany** | **France** | **The Netherlands** | **Sweden** |
| 47,5 – 48,5 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| 48,5 – 49,0 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| 49,0 – 51,0 Hz | Unlimited | Unlimited | Unlimited | Unlimited |
| 51,0 – 51,5 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| Source | VDE AR N 4105: 2018-11;  Paragraph 5.7.1 and table 1 | Arrêté du 9 juin 2020;  Article 36 | Netcode elektriciteit;  Article 3.13 (1) | Föreskrift EIFS 2018:2;  Chapter 3(1) |

Table 7: frequency ranges and minimum time periods for operation

### Admissible active power output with falling frequency

During periods of underfrequency, there is a surplus of consumption compared to generation. It is important that active power output of PGMs at low frequencies is reduced as little as possible. Such drops in active power output are only allowed if the PGM is technologically not able to operate at maximum power, but intentional/voluntary power reduction is never allowed. According to the RfG (Art. 13(4)) and EN 50549-1, the admissible power reduction should be at least 2% per Hz starting at 49 Hz (resulting in a 3% power reduction at 47,5 Hz) and at most 10% per Hz starting at 49,5 Hz (20% at 47,5 Hz). Below 47,5 Hz, a PGM is no longer required to stay connected to the grid.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Permissible reduction | For every frequency drop of 1 Hz below 49,5 Hz, a drop of 10% of the maximum power output is allowed. | For every frequency drop of 1 Hz below 49,0 Hz, a drop of 2% of the maximum power output is allowed. If the frequency is below 49,5 Hz for longer than 30 seconds, a 10% drop of the maximum power output per Hz is allowed. | For every frequency drop of 1 Hz below 49,5 Hz, a drop of 10% of the maximum power output is allowed. | For every frequency drop of 1 Hz below 49,0 Hz, a drop of 3% of the maximum power output is allowed. |
| Source | VDE AR N 4105: 2018-11;  Paragraph 5.7.4.2.3 and figure 13 | Arrêté du 9 juin 2020;  article 39 | Netcode elektriciteit; Article 3.13 (5) | Föreskrift EIFS 2018:2;  Chapter 3(7) |

Table 8: admissible power reduction in active power output with falling frequency

### Resistance to frequency gradients

TSOs must set a value on the rate of change of frequency (RoCoF) up to which a PGM is able to stay connected to the network. This value specifies how fast the grid frequency can change without the disconnection of any PGMs. A large RoCoF can occur after a major system disturbance. When PGMs stay connected to the grid even during this volatile situation, they can help restabilise the network [18]. PGMs are allowed to disconnect from the grid if the given RoCoF values are violated or if the grid frequency exceeds the 47,5 – 51,5 Hz range (see minimum time periods of operation).

The RfG does not set ranges with regard to the RoCoF requirement. Therefore, there is a high variance between member states on the RoCoF values. In The Netherlands the RoCoF values are based on the European standard 50549-1, which sets separate values for different technologies [19]. In Germany, the values are based on an ENTSO-E implementation guidance document that was published before the publication of the 50549 standard. France has not yet set concrete values for RoCoF as of 2021.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| RoCoF requirement | 2 Hz/s for 500 ms; 1,5 Hz/s for 1000 ms; 1,25 Hz/s for 2000 ms | No explicit mention in arrête 9 juin 2020 or Enedis-PRO-RES\_10E  The French grid author decided that no concrete parameters should be set until studies on RoCoF for SPGMs are concluded [20]. | 1 Hz/s for 500 ms for synchronous generators  2 Hz/s for 500 ms for Power Park Modules | 2 Hz/s for 500 ms |
| Source | VDE AR N 4105: 2018-11;  Paragraph 5.7.1 | Netcode elektriciteit;  Article 3.13 (2) | Föreskrift EIFS 2018:2;  Chapter 3 (2) |

Table 9: Resistance to frequency gradients

According to IEEE 1547-2018, PGMs should ride through frequencies of 61.2 – 61,8 Hz and 57.0 – 58.8 Hz for at least five minutes and continuously between a frequency of 58.8 – 61.2 Hz. Within the range of 57.0 – 58.8 Hz, PGMs are not allowed to reduce their active power output further than the active power output before the fault. Additionally, PGMs should be able to ride through a RoCoF of 0.5 to 3.0 Hz/s depending on the size and capabilities of the generator.

## Automatic connection to the network

A PGM should be able to connect to the network automatically if certain conditions specified by the relevant TSO are met. Automatic reconnection to the network after incidental disconnection is only required for PGMs of Type B and C, but is included in some Member States, as well as EN 50549-1 (see section 3.4.4) The conditions for automatic connection are based on the frequency range, voltage range, and the minimum time periods how long these ranges are satisfied. Furthermore, the relevant TSO sets a maximum admissible gradient (% of maximum power output) of increase in active power output per minute. For example, a 20% gradient corresponds to a 20% increase in active power output per minute, resulting in maximum output after 5 minutes.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Frequency | 47,5 – 50,1 Hz | 49,9 – 50,1 Hz | 49,9 – 50,1 Hz | 47,5 – 50,1 Hz |
| Voltage | 0,85 – 1,10 pu | 0,9 – 1,10 pu | 0,90 – 1,10 pu | N/A |
| Minimum time | 1 minute | Not specified | 1 minute | 3 minutes |
| Max. gradient | 10% / min | Not specified | 20% / min | 47,5 – 49,9 unlimited  49,9 – 50,1 Hz 10% / min |
| Sources | VDE AR N 4105: 2018-11;  Paragraph 8.3.1 | Arrêté du 9 juin 2020;  article 46 | Netcode elektriciteit;  Article 3.13 (7) | Föreskrift EIFS 2018:2;  Chapter 3(9) |

Table 10: automatic connection to the network

In the United States, the system operator shall specify the frequency and voltage ranges that need to be met if a PGM wants to connect to the network. If no ranges are defined, the default settings are applicable. The minimum value for voltage shall be set between 88% and 95% of the nominal voltage (default: 91.7%) and maximum between 105% and 106% of the nominal voltage (default: 105%). The minimum value for frequency shall be set between 59.0 – 59.9 Hz (default: 59.5 Hz) and maximum between 60.1 – 61 Hz (default: 60.1 Hz). The minimum time period on how long these ranges need to be satisfied shall be set between 0 seconds and 600 seconds, with a default time of 300 seconds if none is defined by the system operator.

## Miscellaneous

Member States are obliged to implement the requirements mentioned in sections 3.1 to 3.3 for all Type A PGMs. 50549-1 includes additional requirements related to the interconnected transmission system. The following requirements do not need to be transposed in Member States as per RfG, but are implemented in at least one of the four selected countries.

### Undervoltage ride through

Undervoltage ride through (UVRT) is the capability of a PGM to stay connected to the grid during short periods of undervoltage. It is an important element to differentiate between a complete loss and a brief decrease of grid voltage. A PGM not equipped with UVRT turns off for a few minutes if the grid voltage drops below a certain level, even if this drop only occurs for a few seconds. At the local level, the simultaneous disconnection of many PGMs can cause further disturbances to the electricity grid. UVRT is defined in the RfG for PGMs starting at Type B, but it is also recommended for Type A PGMs in EN 50549-1. Figure 1 shows the LVRT curves for storage units in Germany. If the voltage drops below 80% of the nominal voltage, a PGM shall ride through for at least the specified time period, but shall not feed current into the grid.

### Overvoltage ride through

Comparable to UVRT, overvoltage ride through (OVRT) describes the capability of a PGM to stay connected to the grid during short periods of overvoltage. Overvoltage usually occurs after a voltage recovery following a short period of low voltage. This causes the voltage to shortly peak above 115% of the nominal voltage, which can lead to the tripping of equipment [12]. OVRT is implemented in France and Germany based on EN 50549-1. PGMs should stay connected to the grid for at least five seconds when the voltage is between 115 and 120% of the nominal voltage and for 60 seconds when the voltage is between 110 and 115% of the nominal voltage. A PGM shall ride through voltage spikes above 110% of the nominal voltage for at least the specified time period without feeding current into the grid.

Voltage related protection, UVRT, and OVRT capabilities for PGMs according to IEEE 1547-2018 are specified in table 11.

### Post fault active power recovery

Post-fault active power recovery (PFAPR) refers to the ability of PGMs to provide active power after a fault or after a fault-ride-through performance according to conditions set by the network operator. The RfG and EN 50549-1 only mention PFPAR with regard to PGMs of Type B and above. PFAPR was implemented to ensure that generation would resume as quickly as possible after a fault, as to limit the fall in frequency. If electronic equipment (both generation and consumption) would not reconnect simultaneously and would not provide or consume the same amount of active power as before the fault, a new disturbance in grid frequency would occur due to a mismatch in demand and generation. Recent recommendations on the revision of the RfG include applying PFAPR to Type A PGMs as well. Type A PGMs were initially excluded from voltage ride through and PFAPR requirements due to technological constraints and potentially costly implementation, but with the growing share of Type A PGMs, it might be necessary for system security reasons to include these requirements for Type A as well.

Policy papers by the Expert Group “Baseline for Type A Power Generating Modules” and ACER recommend mandating both voltage ride through and PFAPR requirements for all PGMs of Type A and above [6][15]. Of the four researched countries, only Germany has currently implemented PFAPR for Type A PGMs. After the network voltage resumes a value between 85% and 110% of the nominal voltage, a storage unit should resume the pre-fault active power output within 1 second [21].

Within IEEE 1547-2018, the post fault reconnection requirements are identical to connection requirements under normal circumstances. Active power increase shall occur over the course of the enter service period, which is to be determined by the system operator (between 1 and 1000 seconds; default: 300 seconds). The increase in active power output shall increase stepwise with a maximum of 20% per step.

### Post fault reconnection requirements

Post fault reconnection requirements specify the values that need to be met to trigger the reconnection of a PGM after a system fault. Similar to automatic connection under normal circumstances, the PGM should determine that the frequency and voltage levels are within a range specified by the system operator and requirements regarding delay time and maximum active power increase are met. EN 50549-1 sets these parameters starting at Type B PGMs only. For Type A PGMs, only Germany allows the automatic reconnection after tripping under the same circumstances as connection under normal operation.

Post fault reconnection is a more complicated procedure than normal connection (see paragraph 3.3). System restoration after a fault is a coordinated process specified in the ER code [10], whereas reconnection by a PGM happens automatically. Frequency and voltage levels are specified to prevent PGMs of reconnecting during the system restoration process. For instance, during the 2006 European Blackout, wind turbines automatically reconnected to the grid at a frequency of 50.3 Hz, leading to a further increase in frequency up to 50.45 Hz [23]. With strict post fault reconnection requirements as are currently implemented in Germany, Type A PGMs are only allowed to reconnect to the grid if the frequency is below 50.1 Hz for at least one minute (see table 10).

## Conclusions and recommendations

# Distribution system aspects

Distribution system aspects are not within the scope of the RfG and, hence, there currently do not exist mandatory European wide requirements. EN 50549-1 includes a number of requirements related to distribution system aspects. There exists a discrepancy between Member States regarding which aspects are generally covered by national grid codes (e.g. Germany) and Member States in which these aspects are either not defined at all, or defined differently between system operators within the same country (e.g. Sweden).

## Interface protection

According to EN 50549-2, the interface protection has the following objectives [24]:

- prevent the power production of the generating plant to cause an overvoltage situation in the distribution network it is connected to. Such overvoltages could result in damages to the equipment connected to the distribution network as well as the distribution network itself.

- detect unintentional island situations and disconnect the generating plant in this case. This is contributing to prevent damage to other equipment, both in the producers’ installations and the distribution network due to out of phase reclosing and to allow for maintenance work after an intentional disconnection of a section of the distribution network

- assist in bringing the distribution network to a controlled state in case of voltage or frequency deviations beyond corresponding regulation values.

Interface protection may contribute to preventing damage to generation units. To achieve this, it is necessary that at least the voltage and frequency are constantly measured.

### Frequency related protection

PGMs should automatically disconnect from the grid when the grid frequency exceeds certain limits. This is a mandatory requirement for PGMs of type B and above, but has also been implemented for type A in The Netherlands and Germany. In both cases, PGMs should disconnect from the grid if the frequency drops below 47,5 Hz or exceeds 51,5 Hz. Germany requires a disconnection within 0.2 seconds, whereas the Netherlands only demands a disconnection within 2 seconds.

Frequency related protection is considered a mandatory requirement for PGMs in IEEE 1547-2018. If not specified further by the relevant system operator, a PGM shall trip within 300 seconds if the grid frequency drops below 58.5 Hz or exceeds 61.2 Hz and shall trip within 0.16 seconds if the grid frequency drops below 56.5 Hz or exceeds 62.0 Hz. System operators are allowed to broaden or narrow down the frequency thresholds and the maximum time periods before tripping occurs

### Voltage related protection

Similar to frequency related protection, PGMs shall not feed current into the grid if the voltage exceeds predefined voltage levels. EN 50549-1 defines voltage related protection, but does not provide specific voltage levels at which the voltage related protection should be activated. Currently, only Germany and the Netherlands defines a voltage related protection at the low voltage level. In Germany, PGMs shall not feed current into the grid if the voltage drops below 80% or exceeds 110% of the nominal voltage. However, PGMs should still stay connected for a few seconds in accordance with voltage ride through capabilities specified in sections 3.4.2 and 3.4.3. The Dutch grid code specifies that PGMs with a maximum power of 11 kW or higher should disconnect from the grid within 2 seconds if the voltage exceeds 80% or 110% of the nominal voltage and within 0,2 seconds if the voltage is below 70% of nominal voltage.

Voltage related protection, UVRT, and OVRT capabilities for PGMs according to IEEE 1547-2018 are specified in table 11.

### Voltage related active power reduction

High penetration levels of small distributed energy resources can lead to overvoltage and overfrequency events. Similar to the LFSM-O requirement related to overfrequency events, overvoltage can be mitigated by lowering the power injected into the grid [25]. Voltage related active power reduction is considered to be a distribution system aspect and is therefore not included in the RfG. However, EN 50549-1 includes the requirement to allow PGMs to reduce active power output as a function of rising voltage to avoid disconnection due to overvoltage protection (see 4.1.2). Unlike LFSM-O, however, active power reduction is not a requirement during overvoltage events but rather a measure to avoid temporary curtailment due to tripping of the overvoltage protection. Voltage related active power reduction is implemented in France and Germany.

### Island detection

Island detection or anti-islanding is the ability of a PGM to automatically disconnect from the grid during a power outage. Generators without anti-islanding can continue supply electricity into the grid after a power outage, which can lead to hazard to utility workers and damage to electronic equipment. Usually there would be a significant unbalance between the total load and total generation in islanded parts of the network, which would trigger the frequency or voltage protections of the interface and prevent feed in off electricity into the grid. There is however a chance that total load and generation are close enough to each other to not trigger interface protection. Further means to detect unintentional islands may be required by the DSO, but there is currently no standardised method given in European standards nor the implementation of the RfG in national grid codes.

Islanding detection and the subsequent disconnection from the grid is a mandatory requirement in the German grid code, which states that PGMs should be able to detect islanding and disconnect from the power generation system within 9 seconds [22]. In the US, a PGM shall be able to detect an unintentional island, discontinue feeding current back into the grid, and disconnect from the system within two seconds in accordance with IEEE 1547-2018. The standard does however not specify what anti-islanding method is to be used, but similar to EN 50549 mentions that reliance on voltage and frequency related protection is insufficient.

## Voltage control

### Voltage ranges and minimum time periods for operation

Similar to frequency ranges and minimum periods for operation, this requirement can be implemented to avoid a massive simultaneous disconnection of a large amount of PGMs. Minimum operation time based on voltage ranges is mentioned in the RfG for Type D PGMs only. However, EN 50549-1 also define voltage ranges and minimum periods for operation. According to this standard, PGMs shall be able of operating for an unlimited period if the voltage at the connection point is between 85% and 110% of nominal voltage. Beyond these limits, the requirements for voltage ride through and voltage related protection shall apply accordingly. The German grid code complies with this requirement. In France, voltage ranges are also implemented. However, unlimited operation time is only required between 90% and 110% of nominal voltage [8]. Unlimited operation is mandatory between 88% and 110% of nominal voltage according to IEEE 1547-2018.

### Reactive power capabilities

Voltage regulation at low voltage is one of the key challenges related to the energy transition. Increases in loads and power generation units connected to the low voltage grid (e.g. residential solar PV, EV charging, heat pumps) are increasingly leading to alarming voltage fluctuations. System operators have the obligation to keep the voltage within certain limits (for in depth information on this matter, see chapter 5), for which they can deploy reactive power. Reactive power can either be injected to raise voltage or absorbed to lower voltage.

Historically, system operators did not need to control reactive power flows at the low voltage grid, as harmonization of power factors (i.e. the ratio between real power and apparent power) was deemed sufficient to deal with voltage fluctuations. High power factors would ensure that reactive power into the grid as a whole would be minimized [15]. Power factors are not further specified for Type A PGMs in the RfG, but EN 50549-1 prescribes a power factor from 0.90 underexcited to 0.90 overexcited.

Member States can also mandate that PGMs should be capable of injecting or absorbing reactive power at maximum capacity at varying voltage levels (U-Q/Pmax) and at varying power outputs (P-Q/Pmax). Both modes define the boundaries in which a PGM shall be capable of providing reactive power. Figure 2 shows the U-P-Q/Pmax and U-Q/Pmax profiles respectively as depicted in the standard EN 50549-2. Dynamic reactive power capability is defined for Type C and D PGMs in the RfG. Of the researched Member States, only Germany has defined dynamic reactive power capability for Type A PGMs.

According to IEEE 1547-2018, PGMs should be able to inject and absorb 44% of the apparent power rating, which corresponds to a power factor of approximately 0.90.

### Reactive power control

Additionally, Member States can implement different control modes to enable automatic reactive power control. System operators can require the mode used for the contribution to voltage control. The standards EN 50549-1/-2 mention five different control modes, but only one shall be active at any given time.

#### Q(U): voltage related control mode

PGMs should be able to control reactive power as a function of the measured voltage via volt-var curves (see figure 3). The necessary reactive power output shall be calculated either by measuring the average of the voltages from each phase to neutral or phase to phase or by calculating the reactive power for every phase independently. The PGM responds to measured deviations from the nominal voltage by injecting or absorbing reactive power. The impact of distributed energy resources on local voltage levels can be mitigated if the DER can automatically correct voltage deviations via reactive power absorption/injecting based on voltage. Q(U) control is the preferred method of voltage control in Germany, based on a report by the national regulatory authority VDE-FNN [27], but is only applied to three-phase current systems.

#### Q setpoint: constant reactive power mode

The system operator can obligate the PGM to provide a fixed amount of reactive power (either injection or absorption). Q setpoint is easier to configure than other control modes, but may lead to unnecessary active power curtailment and is more difficult to coordinate.

#### Cos φ setpoint: constant power factor mode

With this control mode, generation operates with a fixed power factor such that reactive power is proportional to active power (usually at a power factor of 0.95 – 0.98) and the reactive power provision remains constant over time. The target power factor shall be specified by the relevant system operator.

#### Q(P) (active power – reactive power mode) and Cos φ (P) (watt – power factor operational function)

The Q(P) mode controls reactive power as a function of the active power output following a specified watt-var curve. Cos φ (P) controls the power factor as a function of the active power output following a specified watt-pf curve. Of the researched countries, only Germany implemented the Cos φ (P) control mode. According to this requirement, PGMs should be able to operate with a power factor of at least 0.9 underexcited (i.e. absorb reactive power) at maximum capacity and at 1.0 at 0.5 times the maximum capacity, following a linear curve (see figure 4).

|  |  |
| --- | --- |
| **Control mode** | **Implementation** |
| Q(U) | EN 50549-1/-2: included  Germany: included for three phase only.  The Netherlands: only for PGMs connected to MV and HV grids and only for voltage levels *below* the nominal voltage.  IEEE 1547-2018: mandatory for all PGMs. |
| Q setpoint | EN 50549-1/-2: included  IEEE 1547-2018: mandatory for all PGMs. |
| Cos φ setpoint | EN 50549-1/-2: included  Germany: included  IEEE 1547-2018: mandatory for all PGMs, default setting for PGMs. |
| Q(P) | EN 50549-1/-2: included in 50549-2. Excluded in 50549-1.  IEEE 1547-2018: included. Default: if active power is > 0.5 times maximum active power, reactive power injection/absorption should be up to 44% according to a linear curve. |
| Cos φ (P) | EN 50549-1/-2: included  Germany: included |

Table 12: implementation of reactive power control modes in selected Member States and standards.

## Conclusions and recommendations

# Power quality

Managing power quality is important in order to ensure the safety, performance, and cost-effectiveness of the grid. Issues with power quality can lead to energy losses, overload, and/or damage to and disconnection of electronic equipment [26]. Electronic equipment should be immune to electromagnetic disturbances whilst not introducing intolerable electromagnetic disturbances themselves.

Power quality aspects fall outside the scope of the RfG, so no specific requirements are given in the EN 50549-1/-2 standards. Rather, the standards only specify that generating plants must not cause voltage rises, harmonic distortions, and flicker exceeding certain limits [24]. Instead, the standards reference a multitude of other standards on power quality, including EN 50160 and the IEC 61000 series. The IEEE standard 1547-2018 on the interconnection of distributed energy resources (used in the United States) also includes power quality requirements based on the IEC 61000 series and the standard IEEE 1453 (which is itself based on IEC 61000). Power quality requirements are therefore highly comparable between the European and American contexts.

EN 50160 describes the voltage characteristics of the electricity supplied by a system operator at a customer’s installation. System operators are responsible for keeping the grid voltage and frequency within admissible ranges and equipment connected to the grid should be immune to disturbances specified in the standard to ensure grid security. Other PQ-related standards comply with the thresholds specified in the EN 50160 standard, most notably IEC 61000-2-2. The following power quality aspects are described in these standards:

*Full list of Power Quality requirements is a work in progress.*

# List of tables and figures

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Type A | 0,8 kW – 135 kW | 0,8 kW – 1 MW | 0,8 kW – 1 MW | 0,8 kW – 1,5 MW |
| Type B | 135 kW – 36 MW | 1 MW – 18 MW | 1 MW – 50 MW | 1,5 MW – 10 MW |

Table 1: Type A and B thresholds [7]

|  |  |  |  |
| --- | --- | --- | --- |
| **Requirement** | **RfG: Type A** | **EN 50549-1** | **IEEE 1547-2018** |
| **Transmission system aspects** | | | |
| *Emergency state – over- and underfrequency* | | | |
| Limited frequency sensitive mode – overfrequency | Included | Included | Included |
| Limited frequency sensitive mode - underfrequency | Included for storage facilities | Included for storage facilities | Included |
| Logic interface to cease active power | Included | Included | *TBD* |
| *Continued operation* | | | |
| Frequency ranges and minimum time periods for operation | Included | Included | Included |
| Admissible active power reduction with falling frequency | Included | Included | Included |
| Resistance to frequency gradients | Included | Included | Included |
| *Automatic connection to the network* | | | |
| Required frequency and voltage ranges | Included | Included | Included |
| *Miscellaneous* | | | |
| Frequency related protection |  | Included | Included |
| Undervoltage ride through |  | Included | Included |
| Overvoltage ride through |  | Included | Included |
| Post fault reconnection requirements |  | Included (Type B only) | Included |
| Post fault active power recovery |  | Included | *TBD* |
| **Distribution system aspects** | | | |
| Anti-islanding |  | Included | Included |
| Voltage related active power reduction |  | Included | Included |
| Voltage ranges and minimum time periods for operation |  |  | Included |
| Voltage related protection |  | Included | Included |
| Reactive power capabilities |  | Included | Included |
| Reactive power control |  | Included | Included |
| **Power Quality** | | | |
| Power quality requirements | Power quality requirements are outside the scope of RfG/50549-1. PQ requirements are described in standards EN 50160 and the IEC 61000 series. | | Included |

Table 2: overview of grid connection requirements for PGMs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Frequency threshold | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,2 – 50,5 Hz  Default: 50,2 Hz | 50,5 Hz |
| Droop % | 2% to 12%  Default: 5% | 3% to 12%  Default: 5% | 4% to 12%  Default: 5% | 8% |
| Further actions | Further reduction in active power | N/A | Operation to continue | Operation to continue |
| Sources | VDE AR N 4105: 2018-11;  Paragraph 5.7.4.2.3 | Arrêté du 9 juin 2020;  Article 37 | Netcode elektriciteit;  Article 3.13 (4) | Föreskrift EIFS 2018:2;  Chapter 3(3) – 3(6) |

Table 3: LFSM-O requirements in selected countries.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency | Above 50,2 threshold  (DE/FR/NL) | Minimum acceptable decrease in active power output (DE/FR/NL) | Above 50,5 threshold (SE) | Minimum acceptable decrease in active power output (SE) |
| 50.0 | 0 | 0% | 0 | 0% |
| 50.1 | 0 | 0% | 0 | 0% |
| 50.2 | 0 | 0% | 0 | 0% |
| 50.3 | 0.1 | 4% | 0 | 0% |
| 50.4 | 0.2 | 8% | 0 | 0% |
| 50.5 | 0.3 | 12% | 0 | 0% |
| 50.6 | 0.4 | 16% | 0.1 | 2.5% |
| 50.7 | 0.5 | 20% | 0.2 | 5% |
| 50.8 | 0.6 | 24% | 0.3 | 7.5% |
| 50.9 | 0.7 | 28% | 0.4 | 10% |
| 51.0 | 0.8 | 32% | 0.5 | 12.5% |
| 51.1 | 0.9 | 36% | 0.6 | 15% |
| 51.2 | 1.0 | 40% | 0.7 | 17.5% |
| 51.3 | 1.1 | 44% | 0.8 | 20% |
| 51.4 | 1.2 | 48% | 0.9 | 22.5% |
| 51.5 | 1.3 | 52% | 1.0 | 25% |
| > 51.5% | N/A | 100% | N/A | 100% |

Table 4: minimum mandatory decrease in active power output at increasing frequency.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Frequency threshold | 49.8 Hz | N/A | 49.8 Hz | N/A |
| Droop % | 2% |  | 1% |  |
| Disconnection from grid | Immediately at 47.5 Hz. |  | Immediately at 47.5 Hz.  Within 10s at 49.7 Hz and immediately at 49.3 Hz if it is not capable of moving to generation mode. |  |
| Sources | VDE AR N 4105:  2018-11;  Paragraph 5.7.4.2.3  VDE-AR-N 4142 |  | Tennet: Systeembeschermings- en herstelplan, p. 28  Will be implemented in the Dutch grid code. Article 2.16(3)(f)  See also:  Netbeheer Nederland: BR-2022-1876 |  |

Table 5: LFSM-U requirements in selected countries.

|  |  |  |  |
| --- | --- | --- | --- |
| Frequency | Below 49,8 Hz threshold | Minimum acceptable variation in active power output (NL) | Minimum acceptable variation in active power output (DE) |
| 50.0 | 0 | 0% | 0% |
| 49.9 | 0 | 0% | 0% |
| 49.8 | 0 | 0% | 0% |
| 49.7 | 0.1 | 20% decrease (demand) | 10% decrease (demand) |
| 49.6 | 0.2 | 40% decrease | 20% decrease |
| 49.5 | 0.3 | 60% decrease | 30% decrease |
| 49.4 | 0.4 | 80% decrease | 40% decrease |
| 49.3 | 0.5 | 100% decrease | 50% decrease |
| 49.2 | 0.6 | 20% increase | 60% decrease |
| 49.1 | 0.7 | 40% increase | 70% decrease |
| 49.0 | 0.8 | 60% increase | 80% decrease |
| 48.9 | 0.9 | 80% increase | 90% decrease |
| 48.8 | 1.0 | 100% increase | 100% decrease |
| 48.7 | 1.1 | 100% increase | 10% increase (supply) |
| 48.6 | 1.2 | 100% increase | 20% increase |
| 48.5 | 1.3 | 100% increase | 30% increase |
| 48.4 | 1.4 | 100% increase | 40% increase |
| 48.3 | 1.5 | 100% increase | 50% increase |
| 48.2 | 1.6 | 100% increase | 60% increase |
| 48.1 | 1.7 | 100% increase | 70% increase |
| 48.0 | 1.8 | 100% increase | 80% increase |
| 47.9 | 1.9 | 100% increase | 90% increase |
| 47.8 | 2.0 | 100% increase | 100% increase |
| 47.5 – 47.8 | 2.0 – 2.3 | 100% increase | 100% increase |
| < 47.5 (immediate disconnection) | N/A | 0% | 0% |

Table 6: minimum mandatory variation in active power output at decreasing frequency.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency range | **Germany** | **France** | **The Netherlands** | **Sweden** |
| 47,5 – 48,5 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| 48,5 – 49,0 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| 49,0 – 51,0 Hz | Unlimited | Unlimited | Unlimited | Unlimited |
| 51,0 – 51,5 Hz | 30 minutes | 30 minutes | 30 minutes | 30 minutes |
| Source | VDE AR N 4105: 2018-11;  Paragraph 5.7.1 and table 1 | Arrêté du 9 juin 2020;  Article 36 | Netcode elektriciteit;  Article 3.13 (1) | Föreskrift EIFS 2018:2;  Chapter 3(1) |

Table 7: frequency ranges and minimum time periods for operation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Permissible reduction | For every frequency drop of 1 Hz below 49,5 Hz, a drop of 10% of the maximum power output is allowed. | For every frequency drop of 1 Hz below 49,0 Hz, a drop of 2% of the maximum power output is allowed. If the frequency is below 49,5 Hz for longer than 30 seconds, a 10% drop of the maximum power output per Hz is allowed. Power Park Modules are not allowed to drop their power output. | For every frequency drop of 1 Hz below 49,5 Hz, a drop of 10% of the maximum power output is allowed. | For every frequency drop of 1 Hz below 49,0 Hz, a drop of 3% of the maximum power output is allowed. |
| Source | VDE AR N 4105: 2018-11  Paragraph 5.7.4.2.3 and figure 13 | Arrêté du 9 juin 2020 (réseau public d'électricité d'une installation de production d'électricité; article 39 | Netcode elektriciteit, Article 3.13 (5) | Föreskrift EIFS 2018:2. Chapter 3 (7) |

Table 8: admissible power reduction in active power output with falling frequency

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| RoCoF requirement | 2 Hz/s for 500 ms; 1,5 Hz/s for 1000 ms; 1,25 Hz/s for 2000 ms | No explicit mention in arrête 9 juin 2020 or Enedis-PRO-RES\_10E  The French grid author decided that no concrete parameters should be set until studies on RoCoF for SPGMs are concluded [20]. | 1 Hz/s for 500 ms for synchronous generators  2 Hz/s for 500 ms for Power Park Modules | 2 Hz/s for 500 ms |
| Source | VDE AR N 4105: 2018-11;  Paragraph 5.7.1 | Netcode elektriciteit;  Article 3.13 (2) | Föreskrift EIFS 2018:2;  Chapter 3 (2) |

Table 9: Resistance to frequency gradients

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Germany** | **France** | **The Netherlands** | **Sweden** |
| Frequency | 47,5 – 50,1 Hz | 49,9 – 50,1 Hz | 49,9 – 50,1 Hz | 47,5 – 50,1 Hz |
| Voltage | 0,85 – 1,10 pu | 0,9 – 1,10 pu | 0,90 – 1,10 pu | N/A |
| Minimum time | 1 minute | Not specified | 1 minute | 3 minutes |
| Max. gradient | 10% / min | Not specified | 20% / min | 47,5 – 49,9 unlimited  49,9 – 50,1 Hz 10% / min |
| Sources | VDE AR N 4105: 2018-11;  Paragraph 8.3.1 | Arrêté du 9 juin 2020;  article 46 | Netcode elektriciteit;  Article 3.13 (7) | Föreskrift EIFS 2018:2;  Chapter 3(9) |

Table 10: automatic connection to the network

|  |  |  |  |
| --- | --- | --- | --- |
| Voltage range | Response | Minimum ride-through time | Maximum response time to disconnect |
| > 120% | Must trip | N/A | 0.16 seconds |
| 117.5 – 120% | Tripping mandatory after ride-through time | 0.2 seconds | 2 seconds |
| 115 – 117.5% | Tripping allowed after ride-through time | 0.5 seconds | 2 seconds |
| 110 – 115% | Tripping allowed after ride-through time | 1 second | 2 seconds |
| 88 - 110% | Continuous operation | Infinite | N/A |
| 70 – 88% | Tripping allowed after ride-through time | 0.7 – 1.42 seconds | 2 seconds |
| 45 – 70% | Tripping allowed after ride-through time | 0.16 seconds | 2 seconds |
| < 45% | Must trip | N/A | 0.16 seconds |

Table 11: voltage ride through requirements according to IEEE 1547-2018

|  |  |
| --- | --- |
| **Control mode** | **Implementation** |
| Q(U) | EN 50549-1/-2: included  Germany: included for three phase only.  The Netherlands: only for PGMs connected to MV and HV grids and only for voltage levels *below* the nominal voltage.  IEEE 1547-2018: mandatory for all PGMs. |
| Q setpoint | EN 50549-1/-2: included  IEEE 1547-2018: mandatory for all PGMs. |
| Cos φ setpoint | EN 50549-1/-2: included  Germany: included  IEEE 1547-2018: mandatory for all PGMs, default setting for PGMs. |
| Q(P) | EN 50549-1/-2: included in 50549-2. Excluded in 50549-1.  IEEE 1547-2018: included. Default: if active power is > 0.5 times maximum active power, reactive power injection/absorption should be up to 44% according to a linear curve. |
| Cos φ (P) | EN 50549-1/-2: included  Germany: included |

Table 12: implementation of reactive power control modes in selected Member States and standards.

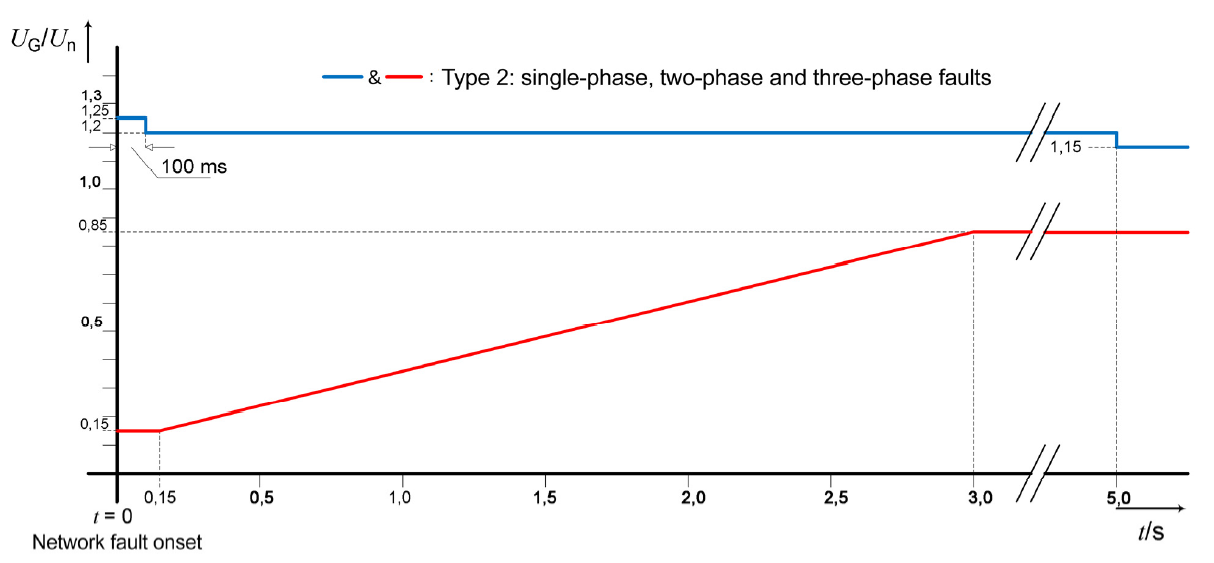


Figure 1: UVRT curve for storage units in Germany

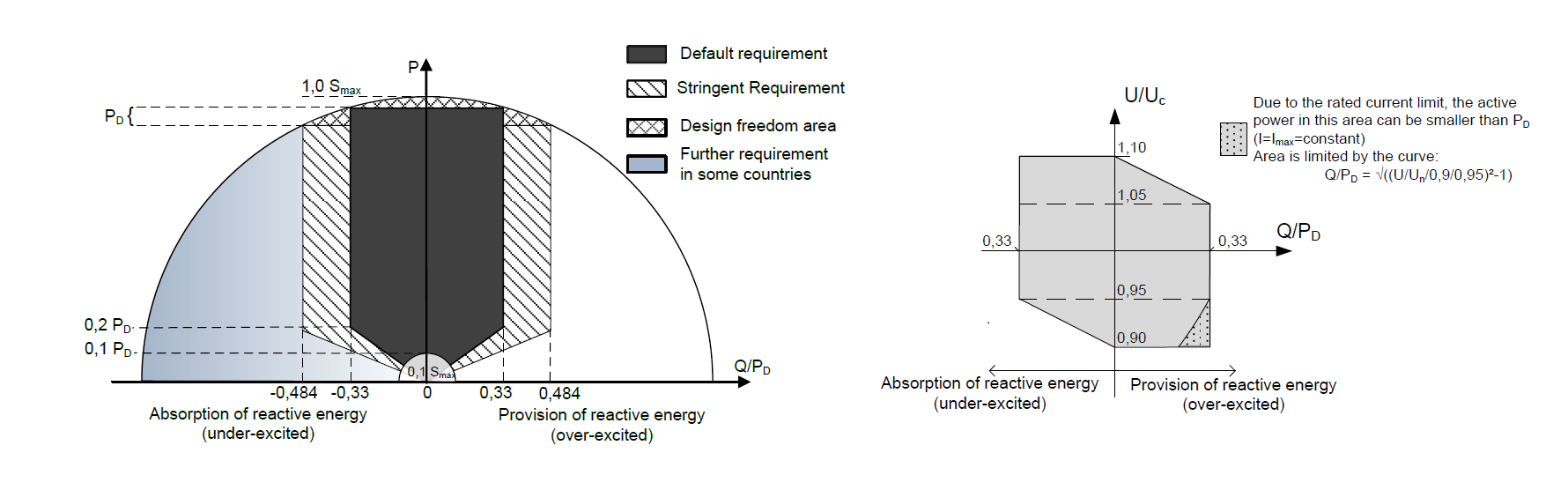


Figure 2: P-Q/Pmax and U-Q/Pmax profiles defined in EN 50549-2.

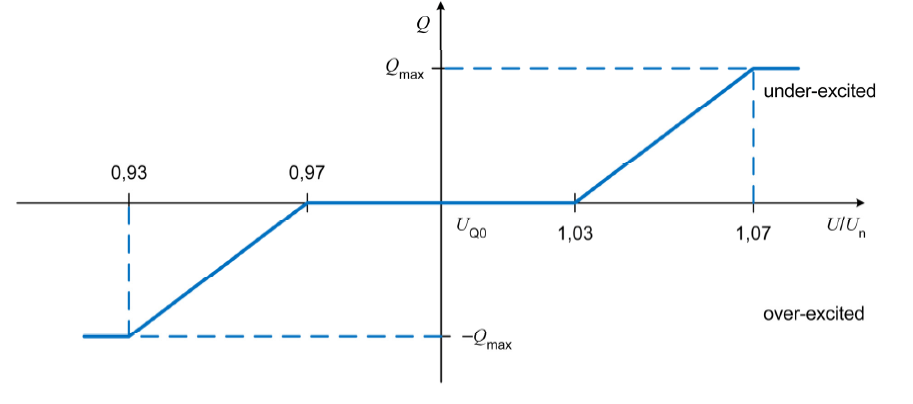


Figure 3: standard Q(U) curve for PGMs in Germany

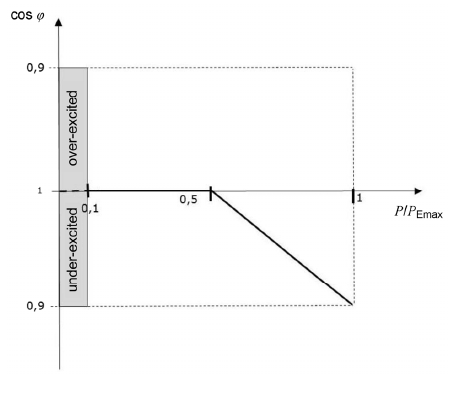


Figure 4: Watt-pf curve for PGMs in Germany

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