Need for grid-forming units in the distribution grid and their impact on protection, automation and control

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Abstract

To achieve a carbon-neutral but still stable power system, the substitution of grid-forming functionalities from big, centralized power plants with directly coupled synchronous generators by decentralized inverter-based generation or storage systems is necessary for inverter-dominated networks. In this context, the requirements for system protection functionalities and the objectives of the grid and plant protection of the German distribution grid are compared. With increasing inverter-based generation and the development of grid-forming capabilities during the next years, the contribution to voltage support and inertia from the distribution grids might also increase. The in parts contradictory timelines and interests of network protection in the distribution grids and of the grid-forming functionalities for the system stability have to be considered from distribution and transmission system operators for future concepts. Potential conflicts and challenges are identified for further discussions, developments and detailed investigations.

Introduction

Need of grid-forming units and the equivalence of inertia provided on distribution grid level

Increasing shares of inverter-based resources (IBRs) are challenging the stability of power systems. Especially the short-term frequency stability is affected through a decrease of synchronous coupled inertia. The reduction of synchronous coupled inertia must be replaced by equivalent behavior of IBRs, the so-called electrical inertia provided by grid-forming inverters (GFM). In the R&D project “Grid Control 2.0” [1] a test scenario used for system split studies was developed and detailed studies and analysis focusing on frequency stability aspects in inverter-dominated grids were conducted in [2].

For the considered test case, the results indicate a limited possible share of conventional grid-following inverters (GFL): even with fine-tuned parameters of grid supporting functionalities not more than 70% shares GFL could be reached without violating frequency stability criteria. By integrating GFM, the overall inverter share could be increased up to 100% without any frequency deterioration.

Investigations focusing on the inertia provision on different grid levels [3] showed the equivalence of inertia provided on transmission or even low distribution grid level respectively. The important parameter is the electrical distance independent from the grid level. But oscillations between GFM units must be considered.

Use of grid-forming inverters down to the lower levels of the public distribution grid

The need of GFM and how much installed capacity will be required, is the important question for the stability of the future carbon-free power system. In Germany, this question is currently discussed based on the system split event of the continental European power system from November 2006 (Figure 1).

Using this system split event as design case for the network development plan 2035, the four German transmission system operators (TSOs) expect a power unbalance of up to 38 GW which would relate to a rate of change of frequency (ROCOF) value of 4 Hz/s for the north-eastern grid region (green) [4].

To cover such an event without severe blackouts the studies of the TSOs show that in addition to the assets in the transmission system almost all installed distributed energy resources (DER) that will be connected in the coming years should provide inertia, comprising even PV and battery systems on household level in the LV networks. The discussions about the implications are ongoing.

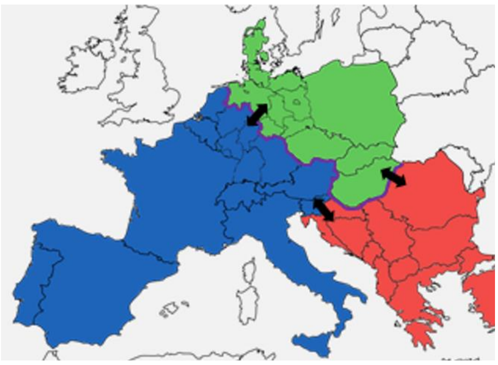

Figure 1. System split of the continental European power system in three regions (green, blue, red) during the event in November 2006 used as design case for stability studies in network development plans [4].

Another driver for GFM on lower grid levels is the resilience of supply that can be supported by microgrids and the capability to operate smaller islanded grid regions.

Roadmaps for GFM application

Several studies, reports and roadmaps are describing the advantages, challenges and research needs regarding the use of GFM in grid operation. We are focusing here on the conclusions drawn from the perspective of distribution grid operation and especially regarding protection.

In [5] the requirements for France regarding the transitions to 100% renewable generation are described using results of the European R&D project MIGRATE (https://www.h2020-migrate.eu/) as reference. Key outcomes are 1) “Even if they still need to be proven at large scale, there is a general scientific consensus that technological solutions to maintain power system strength – and hence system stability – without conventional generation exist in several cases.”, 2) “Specific difficulties are expected in the case of a system with a significant share of distributed solar PV. Further assessment of the impacts of distributed PV on the distribution network is needed as well as their implications for electricity security.” Furthermore, the recommendation is that GFM units should be of sufficient size and preferentially connected to the transmission system, for two main reasons: a) It is easier for the “strength” provided by the grid-forming assets to flow through the grid when impedance is low between the node of interconnection and other grid nodes (But this reason is questioned by the results of [3]); b) The islanding capacities expected from GFM may pose problems of compatibility with distribution grid protections, especially in low voltage networks, where the need to control unit costs leads today to very simplified technical solutions.

From the North-American perspective research needs are described in [6] considering the impact of inverters on grid stability, and evaluating crucial system interactions. Regarding GFM the interaction with voltage regulation schemes and devices is questioned and the need of detailed studies of the effects of GFM on incumbent protection schemes is highlighted.

In a study for Australia [7], potential interactions between GFM and other power system assets are listed. Specifically, a suitable overcurrent rating of GFMs is mentioned if a certain level of fault current needs to be provided to maintain the performance of network protection systems. The study focuses more on higher power ratings but the need of a certain level of fault current applies even more to protection concepts used in the distribution grids.

In summary, there is quite an amount of uncertainty regarding the impact of GFM on distribution grid protection schemes and massive problems with the anti-islanding detection concepts are expected. Recent papers are dealing mostly with the GFM control, stability aspects and the intra-inverter overcurrent protection of the power electronics. But the discussion of the impact of GFM on the grid protection systems is urgently needed to overcome uncertainty and identify potential barriers to reach the goal of 100% renewable generation. This paper presents some of the challenges, including first results from other research groups, to start the discussion in the protection, automation, and control community.

System protection vs line protection – opposing goals

The focus of this chapter is the comparison of the line and the plant protection in distribution grids with the concepts of system protection. The task of the feeder protection is to disconnect defective parts of feeders as fast and selective as possible. To prevent the operating equipment from damage by feeding the fault and to keep the affected area as small as possible.

For plant protection, relays with functionalities like overvoltage, undervoltage, overfreqency and underfrequency are commonly used. Their task are to protect the plant and other operating equipment by disconnecting the plant from a faulty part of the grid.

Depending on the situation, the grid and plant protection devices should react within a time span of some milliseconds to seconds to disconnect feeders and power plants. The following table presents the default values for generation units from the German VDE AR-N 4110 medium voltage grid code [8].

Table 1. Default protection setting for generation units acc. to the German MV grid code [8]

Function	Value [p.u.]	Delay time [ms]
Undervoltage (level 1)	0.80	1000
Undervoltage (level 2)	0.45	300
Overvoltage (level 2)	1.25	100
Underfrequency (level 1)	0.95	100
Overfrequency (level 1)	1.03	5000
Overfrequency (level 2)	1.05	100

Automatic reclosure vs voltage fault-ride-through (FRT) and provision of electrical inertia

Automatic reclosure is widely used to reduce disconnection times. In case of a self-cleared fault, by reclosure the system is back to normal operation. If the arc fault persists, the line will be disconnected again. Depending on the concept, this procedure can be repeated several times. The time range for reclosure actions acc. to German grid operation guidelines is shown in Figure 2 (blue areas with blue triangles).

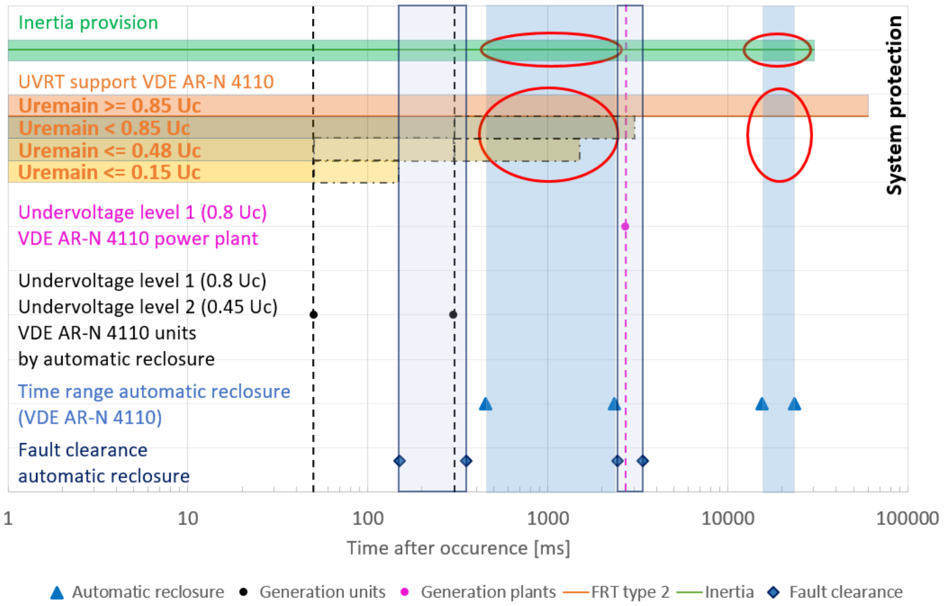

Figure 2. Time overlaps (red circles) of opposing goals for system protection (green and orange) and line/ plant protection (light and dark blue) concepts

For system stability and protection, functions like voltage FRT today and electrical inertia probably in future are required from generators connected to the distribution grids [4], [9]. Grid-following inverters (GFL) can deliver controlled dynamic voltage support. GFM provide inherent voltage support, that can be enhanced with controlled dynamic voltage support, and electrical inertia.

For the voltage FRT capability the German guideline demand the dynamic voltage support for up to 1 minute depending on the voltage deviation. The aim is to keep the voltage in the operating tolerance band or as close as possible to prevent the disconnection of power plants and loads.

Electrical inertia shall respond inherently on frequency changes and limit these until the frequency containment is achieved. Because of the reaction time of the frequency containment reserves (FCR) in the synchronous European continental system, the assumption for the provision of frequency support or electrical inertia is that it should be available for 30 seconds.

The comparison of the time requirements for grid and plant protection with the system protection shows potential conflicts between disconnect and stay connected requirements for power plants. In Figure 2 the system protection aspects inertia provision (green) and dynamic voltage support by low voltage FRT (orange) are displayed over time in logarithmic representation together with the plant protection function undervoltage for generation units and plants with disconnection times and the time range for automatic reclosure with fault clearance. The plant protection could disconnect the units or plants while the provision of inertia or dynamic voltage support is required. The red circles mark areas where system and line/ plant protection requirements are overlapping. In that case, GFM connected within the disconnected area of a failure that should be cleared before reclosing could still be active and feeding the fault.

This situation limits the possibilities for the support of the system stability and isolated but still active network parts leads to the risk of connections with asynchronous islands and feeding into faults. According to the requirements and objectives for a safe and stable power grid operation, the coordination of functions for line, plant and system protection should be further developed.

A further aspect is the undefined behavior of GFM or voltage source inverters during faults. There are different possibilities of the control concerning the behavior in case of FRT and studies show different effects to the critical fault clearing time depending on the control parameters [10], [11].

Potential impact on distance protection schemes

Regarding the impact of GFM on distance protection (ANSI 21), two potential impacts are investigated in recent publications, power swings also on distribution grid level and the influence of current limiting control in the GFM unit on protection zone detection.

In [12] the impact of different control methods and current limiting approaches is described. There are just minor differences between three main control methods but the differences of the three studied current limiting approaches to protect the power electronics are significant. A line-to-line (LL) fault is investigated and only the virtual impedance approach leads to correct detection of the protection zone. Further research is needed including other fault types, the test of relays from different manufacturers and the system behavior when IBRs with both control modes, GFL and GFM, are present.

Power swings are likely to increase with multiple distributed GFM. Exemplary configurations are discussed in [2] and in [13] considering a line with GFM units feeding from both ends and possibly also with intermediate in-feed. Power swing detection is a well-known feature for transmission line protection. How it can be utilized also for distribution lines has to be investigated in more detail. In general, a negative impact on sensitivity and selectivity is expected.

Voltage critical situations

To prevent a voltage collapse in voltage critical situations, one recommended measure is to decrease the load by reducing the voltage level in the distribution grid. Especially for networks with a high share of resistive loads, a voltage less than the nominal voltage reduces the demand of power. GFM and some

GFL with grid-supporting functionalities will control the voltage at their local point of connection. In this case, these units can jeopardize the centrally initiated voltage stability measure. Test cases are investigated in [12]. Emergency actions must be adapted to this situation.

Blinding

Blinding is the reduction of a fault current seen by an upstream protection device, e.g. by fault current contributions or voltage control between the fault location and the protection device. The fault current contribution from distributed energy resources (DER) and their potential local voltage control increases the voltage along the faulted line leading to a decreased fault current from the upstream network.

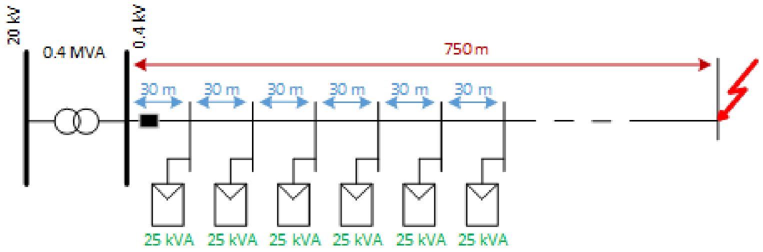

Figure 3. Investigation of the blinding effect in a typical German low voltage feeder with DER

In [15] the blinding effect was investigated as a possible problem for low voltage (LV) grids with fuses as protection devices. A reduced fault current though a fuse causes a longer tripping time. To keep the fault current seen by the fuse sufficiently high, following the German LV grid code DER connect to LV lines have to limit the current to 10% of the nominal current or less (so called ‘zero power mode’ (ZPM)), if the voltage drops under 80% of the nominal voltage.

But with the increase of DER connected to the low voltage grids including GFL and GFM the voltage at the point of connection of the DER will be kept above 80%, nonetheless. This leads to a higher current at the fault location but a lower current at the upstream protection device. In a worst-case scenario for a LV feeder (Figure 3, designed acc. to common German grid planning guidelines), between the fault location at 750 m and the transformer, six IBRs are connected. Each with an apparent power of 25 kVA and the distance between them of 30 m.

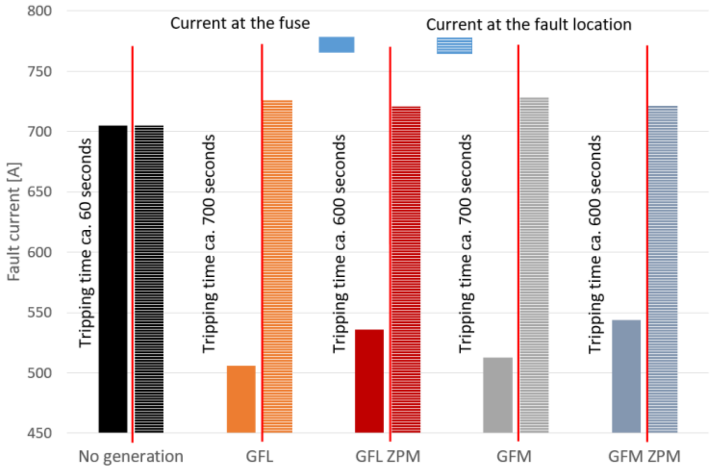

Figure 4. Fault currents at the beginning of the line/ fuse location (solid) and at the fault location (striped) and resulting tripping time of the fuse

Without the DER, the current at the fault location is equal to the current through the fuse. For a fault at 750 m distance, the fuse would clear the fault after 60 seconds. With DER, the current at the fault location is a little bit increased while the current at the fuse is significantly reduced. The results for GFM and GFL are nearly the same even for ZPM or full dynamic voltage support. The fault clearing time with blinding by the IBRs is ca. 10 times higher. Blinding can become a problem with increased numbers of

DER and dynamic voltage support by GFL or GFM reinforces this effect. Again, system needs like voltage FRT and local line protection can have opposing goals.

Islanding detection

A major concern with the integration of GFM into the low-level distribution grid is their effect on today's islanding protection concepts. Unintentional islanding describes the disconnection of a grid section in a fault sequence and random uncontrolled continued operation of the section disconnected from the interconnected grid. This condition should be avoided, especially at the LV level, which is why today's existing converters are equipped with procedures to detect this and consequently disconnect from the grid. It is assumed that GFM technology promotes the danger of the formation and uncontrolled continued operation of these islanded grids. Therefore, the impact of their future grid integration was investigated.

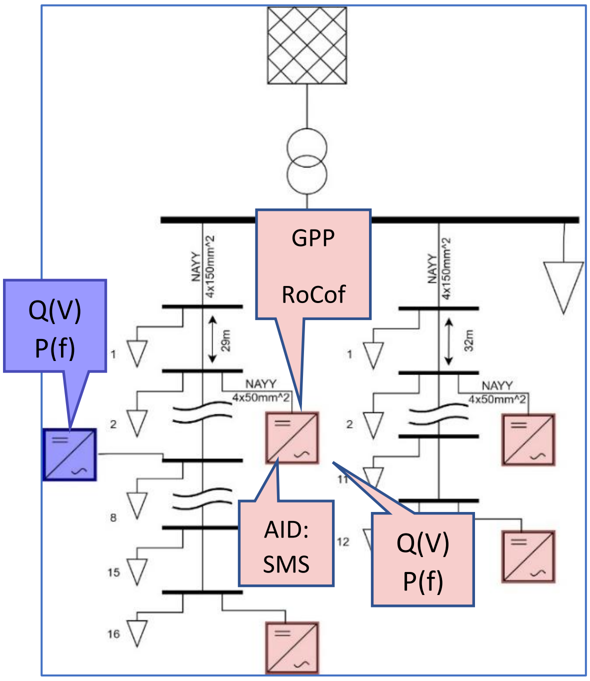

Figure 5. Test setup for evaluating the effect of grid-forming control (blue) without detection on the ability of existing plants (red) to detect islanding.

Methodology: The effect of grid-forming control is investigated in a simulation model that represents a low-voltage grid section. Several conventional grid-following inverters with static grid support and state-of-the-art islanding detection methods are integrated into this section. The correct behavior of this arrangement in the islanding case under varying output conditions is investigated by means of series tests. The benchmark for this is the so-called non-detection zone (NDZ), which summarizes all cases in which islanding could not be detected. Subsequently, an inverter with grid-forming control but without its own detection procedure is integrated into the grid and the test series is repeated. The comparison of the NDZs provides a qualitative statement about the effect of integrating grid-forming systems without their own detection on the ability of the existing systems to detect islanding. Figure 5 outlines the model structure and is explained in more detail in [1].

The presence of GFM increases the probability of islanding and reduces the effectiveness of the investigated passive islanding detection methods of existing plants in the study model.

First, the functioning of passive detection and the effect of instantaneous power differences occurring at the time of islanding were investigated. For this purpose, the active detection was deactivated and the active and reactive power (ΔP, ΔQ) flowing into the grid section at the time of islanding which then abruptly ceases with the islanding, was varied by adjusting the loads within the scope of a test series. After disconnection of the grid section, the time until disconnection of the DER from the grid section and the cause of the disconnection were recorded. If the disconnection does not take place within 5 s after the grid disconnection, the islanding detection is deemed unsuccessful, and the case is attributed to the NDZ. The result is shown in Figure 6 on the left. The NDZ is located around the area of minimum exchange power with the interconnected grid. In this area, the distortions in frequency and amplitude due to the sudden power jump during disconnection are so small that the islanding cannot be detected by the passive detection.

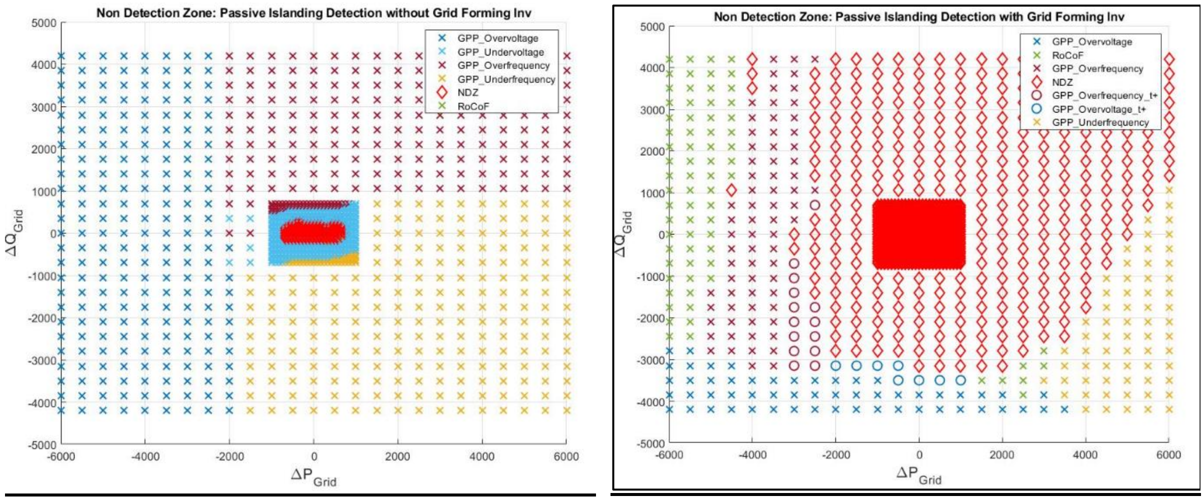

Figure 6. Non-detection zone (red) for passive islanding detection without GFM (left) and with GFM (right).

If a GFM without its own detection method is integrated into this grid section and the test series is repeated, the graph on the right in Figure 6 results. It shows a strong increase in the NDZ and thus a reduction in the effectiveness of passive detection methods of GFL in the presence of a GFM. This is because the ability of the GFM to deliver power instantaneously dampens the frequency and amplitude gradients occurring during islanding. As a result, the island can stabilize itself in a far greater number of initial conditions.

The presence of grid-forming systems stabilizes formed islands and reduces the effectiveness of active islanding detection methods in the study model.

After the formation of an unintended island, active detection procedures should destabilize it in a targeted manner. To investigate the effect on this, the active detection is additionally activated on the GFM (SMS procedure). To ensure the safe formation of the islanding, the exchange power is minimized in each case during islanding. Critical properties of the network load, which usually have an influence on the effectiveness of the detection, are varied via the test series. These are the quality and the resonance frequency of the total grid load in the model. As above, an unsuccessful destabilization and no disconnection of the inverters due to a violation of the frequency or voltage limits by the plant protection within 5 s is attributed to the NDZ. The result is shown in Figure 7.

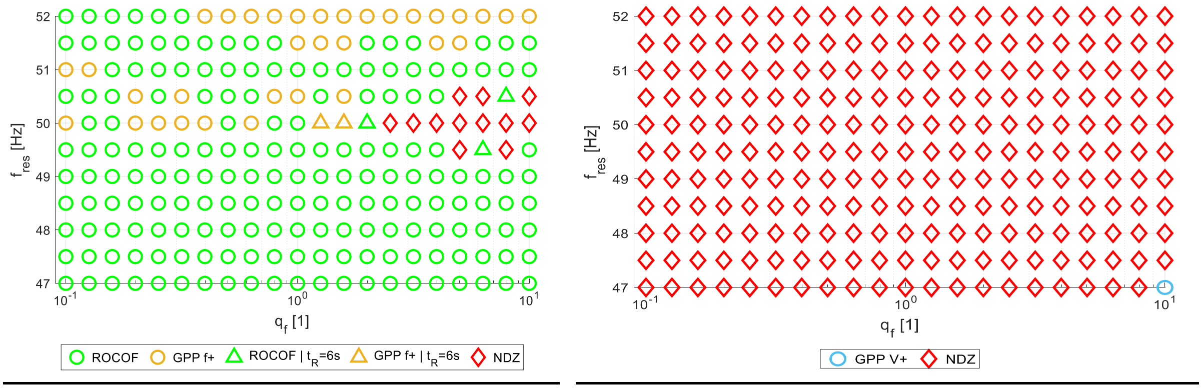

Figure 7. Non-detection zone (red) for active islanding detection without GFM (left) and with GFM (right).

In the scenario on the left, which is based solely on GFL, the NDZ is divided into different areas. As shown in [16], the NDZ is mainly located in the area of high-quality loads and a resonant frequency close to the grid frequency. Furthermore, a small NDZ forms in the range of almost purely resistive loads whose remaining imaginary part resonates around the nominal grid frequency of 50 Hz. The method under consideration can only exert a small influence on this. However, a successful islanding is given in all other, more probable cases.

If a GFM without its own detection is added as a disturbance, the picture on the right graph results. As can be seen, the active islanding detection fails in almost all cases. The NDZ here extends quite evenly over all load grades, but the critical resonance frequency is lower for low quality loads than for increasing quality. The results indicate that a significantly higher number of semi-stable island grids can be expected with the mere presence of GFL. As described in more detail in [1], the reason for this is the regulation of the grid voltage by the new inverter type, which is actively oriented towards keeping it within the permissible range. This violates an essential basic assumption of many frequency shift and related methods, which assume special properties of the characteristics of a purely passive load through which the grid voltage is essentially shaped.

In conclusion, if the integration of GFM is done without an adapted islanding detection procedure suited to the special characteristics of grid-forming control, a significant increase in islanded grids should be expected. The reasons for this are manifold, with the highly dynamic characteristics of GFM actively dampening grid disturbances on which state-of-the-art passive islanding detection is triggered. Meanwhile, the active control of voltage violates operation principles of current active islanding detection techniques that are built for optimal operation on passive loads only, on which all present procedures are tested. This motivates the need for adapted detection techniques for GFM that would need to work in existing grid infrastructure in conjunction with GFL. One of such approaches is introduced in [17] and will be further developed in the course of the recently started German joint R&D project “Verteilnetz 2030plus”.

Conclusion and outlook

Distributed energy resources with grid-forming behavior are likely to be connected in higher numbers to the distribution grid. Drivers are the needs of inertia with a system split scenario as possible design case and the additional resilience of supply provided by microgrids. This development challenges protection and control approaches designed for systems with synchronous generators connected to the transmission system as main source. Some challenges are shown, where especially the impact on distance protection and on blinding and islanding detection needs thoroughly investigation because of their widespread application and impact on personnel safety.

Further effects of GFM are a potential reduction of harmonics in the grid. Depending on the hardware, GFM can compensate harmonics in the positive, negative and zero sequence. While this is in general positive, the effect on harmonic-based fault detection or blocking concepts must be researched.

The recently started German R&D project "Safe and stable operation of inverter-dominated distribution grids – Verteilnetz 2030plus" addresses the critical aspects of stable and secure distribution grid operation in the target year 2030 with a high share of decentralized renewable energies and grid-forming properties. Obstacles to the widespread use of grid-forming control methods at all levels of the distribution grid will be described in detail to come up with possible solutions.

The authors would like to use this opportunity to start the discussion and welcome any comments and suggestions which other issues may arise from the opposing goals of system and grid protection, and specifically because of high shares of grid-forming units in the distribution grid.

Acknowledgement

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