IRENA

International Renewable Energy Agency

SCALING UP VARIABLE RENEWABLE POWER: THE ROLE OF GRID CODES

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Abbreviations

AC	Alternating Current
AEMO	Australian Energy Market Operator
AEMC	Australian Market Energy Commission
BDEW	German Association of Electricity and Water Suppliers
DC	Direct Current
DSO	Distribution System Operator
EEG	Erneubare Energien Gesetz (German Renewable Energy Act)
ENTSO-E	European Network of Transmission System Operators for Electricity
FRT	Fault Ride Through
Hz	Hertz (unit of frequency)
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
kW, MW, GW	Kilowatt, Megawatt, Gigawatt (units of power)
kV	Kilovolt
LVRT	Low Voltage Ride Through
NEM	National Electricity Market
NC RfG	Network Code Requirements for Generators
P	Active Power
Q	Reactive Power
SNSP	System Non-Synchronous Penetration
SONI	Systems Operator for Northern Ireland
TC 2007	Transmission Code 2007
TSO	Transmission System Operator
TWh	Terawatt-hour
VDE	German Association for Electrical, Electronic and Information Technologies (Verband der Elektrotechnik, Elektronik und Informationstechnik)
VRE	Variable Renewable Energy

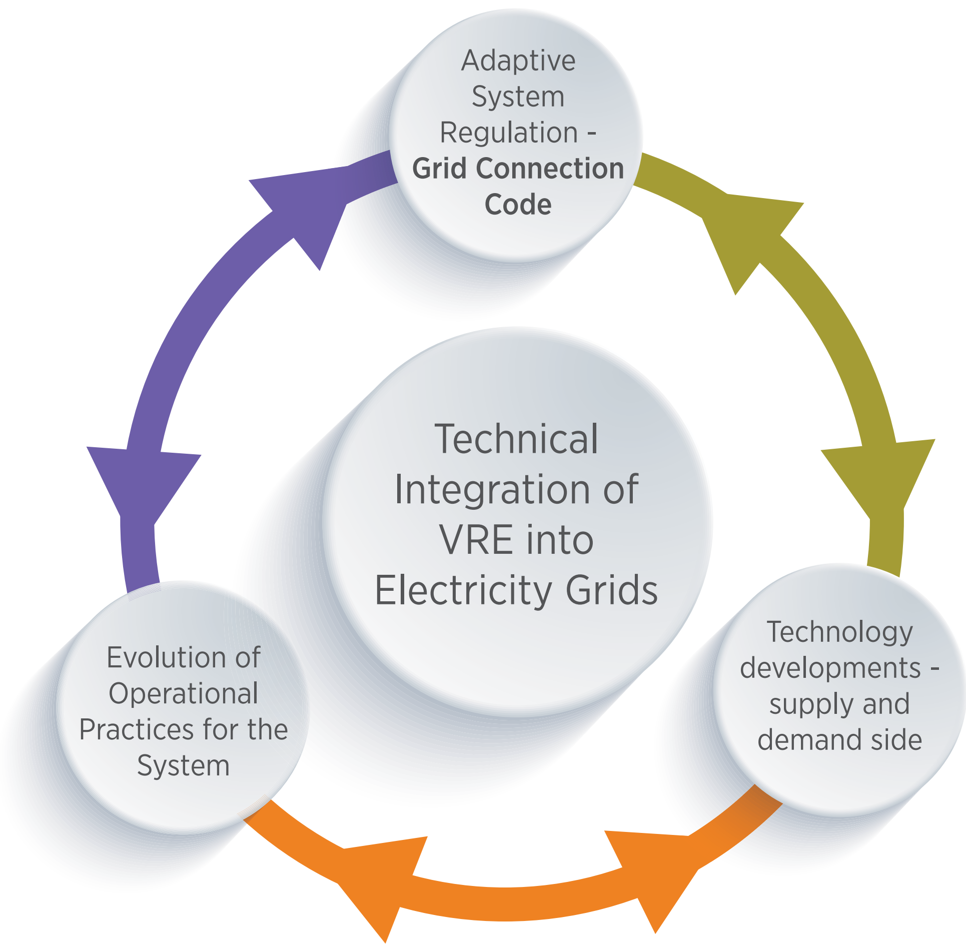
Executive Summary

Executive Summary

The power sector globally is accelerating its transition towards a sustainable energy regime. Since 2011, over 100 gigawatts (GW) of annual capacity additions have been from renewables - more than fossil fuel and nuclear power additions combined. The share of renewables in total electricity production in 2014 exceeded 22%. Hydropower accounted for 16.4% and variable renewable energy (VRE) for 3.6% i.e. solar photovoltaic (PV) and wind. A number of countries already have a significantly higher individual share of VRE than the global figure. Denmark, Spain, Ireland and Germany, for example, each have a share of more than 15%. The International Renewable Energy Agency (IRENA) analysis also indicates that the global share of VRE can be expected to increase by as much as 20% by 2030.

Grid codes are essential for the successful integration of VRE. For the operation of power systems, VRE generators pose challenges that contrast with conventional generation. In response to these challenges, VRE generation technology is rapidly developing, accompanied by enabling technologies like storage and control systems, and facilitating new operational practices for power systems. These technological and operational developments create greater flexibility for operating electricity networks and enable a higher share of VRE. Some rules have to be established for all actors to ensure that electricity service for consumers secure while deploying new technologies and adopting new operational practices. If VRE is to be successfully integrated into electricity networks, then all three components need to be considered: technology, operation and regulation.

Figure 1: Links between technical aspects of electricity systems

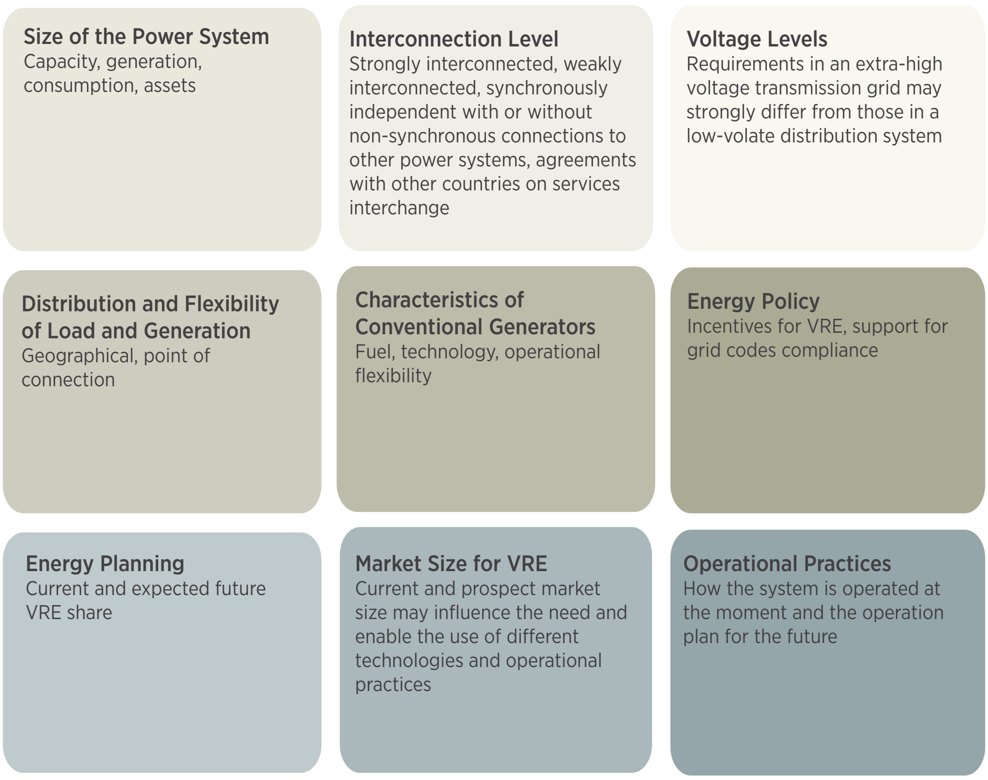


Grid codes provide the rules for the power system and energy market operation, ensuring operational stability, security of supply and well-functioning wholesale markets. A set of grid codes can include, for instance, connection codes, operating codes, planning codes, market codes. This report provides guidance to regulators, policy makers, system operators and other stakeholders on how grid connection codes should be developed and implemented. It considers the country context with a view to enabling a higher share of VRE in the power system.

The function of a grid connection code covering VRE is to provide technical requirements for wind and PV plants when connecting to a country's electricity grid. This helps to ensure the fair treatment of generator owners and operators concerning grid connection while maintaining system stability and reliability. The process of developing a national VRE grid code should include the following elements: preparation of technical studies, data collection and assessment of country-specific aspects; expert draft of the grid code; stakeholder consultation on the draft; grid code endorsement; implementation; revision based on policy changes and experience after employing the grid code.

It is helpful to use previous experience when developing a VRE grid code. Nevertheless, the VRE grid code of another country or region cannot be adopted word for word. Many of the requirements for the connection of VRE generators depend on the specific needs and conditions of the local power system. Considerations to take into account when developing the VRE grid code are presented in the figure below.

Figure 2: Aspects of grid connection code development



The nuances arising as a result of national context when defining the technical requirements of VRE grid codes are illustrated in the country case studies in this report. For example, Ireland has a high share of wind power and limited interconnections so the Irish grid code pays particular attention to frequency control requirements. With a significant penetration of PV systems in low voltage networks, Germany is concerned with reactive power capabilities in distribution systems in its VRE grid code. In the case of Australia, it is shown that a country might have different requirements for different sub-regional grids. In the case of Barbados, where the VRE share is still low, the code does not consider requirements for fault ride through (FRT) or frequency control requirements. However, in view of the national energy plans, the code is being revised at the moment.

Many requirements can be harmonised internationally, enabling countries to pool their resources in areas such as certification. This also makes it easier for manufacturers to access more markets, resulting in lower costs to consumers. The use of international standards to prepare VRE grid codes is another relevant instrument for harmonising requirements, as well as a valuable platform for experts to exchange international experiences and document good practices. The integration of regional power markets also requires regulatory efforts through, for example, regional grid codes like the Nordic Grid Code and European Network of Transmission System Operators for Electricity (ENTSO-E) Network Codes. These regional grid codes do not replace national grid codes but instead provide a common framework for minimum requirements that all national grid codes should meet.

Enforcing technical requirements in VRE grid codes means using mechanisms to verify compliance with the codes. There are different strategies with differing costs and degrees of feasibility depending on country context. These mechanisms include, for example, on-site inspection, use of certification systems or verification of whole plants instead of verification of each and single unit in a plant.

Policy-makers and regulators have to support the development and implementation of VRE grid connection codes in association with the national renewable energy goals, by:

- **Ensuring that grid connection codes include appropriate requirements for VRE.** Electricity system studies can play a role in the identification of appropriate requirements. Also other sources of information regarding local considerations should be used as input for the code.

- **Consulting with all relevant stakeholders**. Grid connection codes have an impact on all actors involved in the power system. Therefore, engagement of all parties will ensure that the codes can be implemented without putting the system security in peril and at the same time the responsibilities are fairly distributed between all actors.

- **Setting a predictable and reliable grid code revision process in place**. This increases system reliability and security by coordinating changes as technology and operation practices develop, also facilitating the future planning of the system.

- **Anticipating technical requirements based on future VRE targets**. Grid codes should not only consider the architecture of today's power system, but already anticipate the future system requirements in line with national VRE goals.

- **Learning from other countries experience.** Identify best practices and lessons learnt from frontrunner countries in integrating a high share of VRE in power systems. However, avoid to implement a carbon copy of other countries grid codes without considering local aspects.

- **Joining regional initiatives to harmonize requirements and share resources.** Regional initiatives and engaging in international standardisation processes may facilitate the development and implementation of grid codes by sharing experiences, deploying regional infrastructure for verification and certification processes, and harmonising requirements resulting in cost reduction due to market scale for technology suppliers.

Grid connection codes help in ensuring that ambitious policy targets for the deployment of VRE are met without compromising the security of the electricity system. All relevant stakeholders follow the same rules as defined in the code, facilitating therefore the operation of the system. As VRE grid codes have evolved hand-in-hand with technology and operational practice, they have also pulled through the deployment of best available technologies for VRE grid integration. What could be considered advanced technologies for integrating VRE a few years ago is now becoming commercially available technology provided by most technology suppliers. A country investing in sound VRE grid code development and implementation will enjoy a guaranteed benefit in terms of reliably integrating high shares of VRE at an affordable grid cost.

Chapter 1

Introduction

1.1 GRID CODE DEFINITION, PURPOSE AND FUNCTION

Grid codes in the widest sense of the term set rules for power system and energy market operation. They enable network operators, generators, suppliers and consumers to function more effectively across the market. This ensures operational stability and security of supply, and contributes to well-functioning wholesale markets. Connection codes, operating codes, planning codes and market codes are a few examples of grid codes.

Figure 3: Different types of grid codes based on ENTSO-E's Network Codes subdivision.

CONNECTION CODES	• Generator Connection Code • Demand Connection Code • HVDC Connection Code
OPERATING CODES	• Operational Security Code • Operational Planning and Scheduling Code • Load Frequency Control and Reserve Code • Emergency Procedure Code
PLANNING CODES	• Generator Planning Code • Network Planning Code
MARKET CODES	• Market Rules Code • Network Capacity Allocation and Congestion Management Code • HVDC Connection Code

This report focuses exclusively on grid connection codes and on the provisions relevant to the connection of VRE generators. For the purpose of this report these refer to wind and solar Photovoltaic (PV) generators of any size. The general term 'VRE grid codes' here specifies the minimum technical and design requirements for VRE generators so that their behaviour is compatible with system stability and safety requirements. By providing appropriate technical and legal rules for VRE generators, VRE grid codes can support the effectiveness of national and regional energy policies for renewables integration.

The grid code is distinct from a country's energy policy. An energy policy provides a framework in which a country addresses some of its energy needs by converting and distributing energy from different sources. A renewables power system policy and regulation can include future targets for the amount of renewable energy to be integrated into the country's power system. Both policies and regulations may provide investment incentives for renewable energy to reach a country's targets, ensuring reliable and affordable development of a sustainable power system. The role of VRE grid codes is to provide technical regulations for the connection of VRE generators to the grid, thereby reducing technical barriers to energy policy fulfilment.

HISTORICAL BACKGROUND

The open formulation and implementation of enforceable grid codes first became necessary with the liberalisation of power systems. While some form of technical regulation for generators has always existed, enforceable grid codes have enabled the co-ordination of multiple individual stakeholders in decentralised power systems. During the unbundling process, vertically integrated utilities were split up into their generation, grid and electricity sales parts and often privatised. The increasing numbers of small, private generators and the separation of generation from operation of the network required clear rules on how these new generators should connect to the public grid.

Grid codes are not only useful in fully unbundled power markets. As technical rules, they regulate grid access and network user operation regardless of whether the power system is operated and supervised by a specific operator or by a vertically integrated utility. The establishment of a grid code is an important step in opening up the power sector to private and especially VRE generators. It increases transparency and provides equal treatment by making the same rules applicable to all. Like other governing frameworks, grid codes have continuously been adapted to changing technologies, system conditions and political aspirations. This is also reflected in the ongoing adaptation of grid codes to enhance the development of regional power markets and integration of renewable energy generators.

The rise of renewables has been driven by the need to reduce carbon dioxide emissions, the plummeting costs of renewable power plants and concerns about energy independence. VRE grid codes seek to ensure that VRE generators contribute towards the safety, stability and reliability of the power system. Many VRE generator grid code requirements show the desire to ensure the fair treatment of conventional and renewable generators in terms of technical requirements on new generation assets of similar sizes. This is achieved by making comparable demands of each in terms of to their contribution to system stability.

The sector transformation and the position of the VRE grid code in the landscape of the power sector are indicated in Figure 4 and Figure 5.

Figure 4: Traditional centralised system.

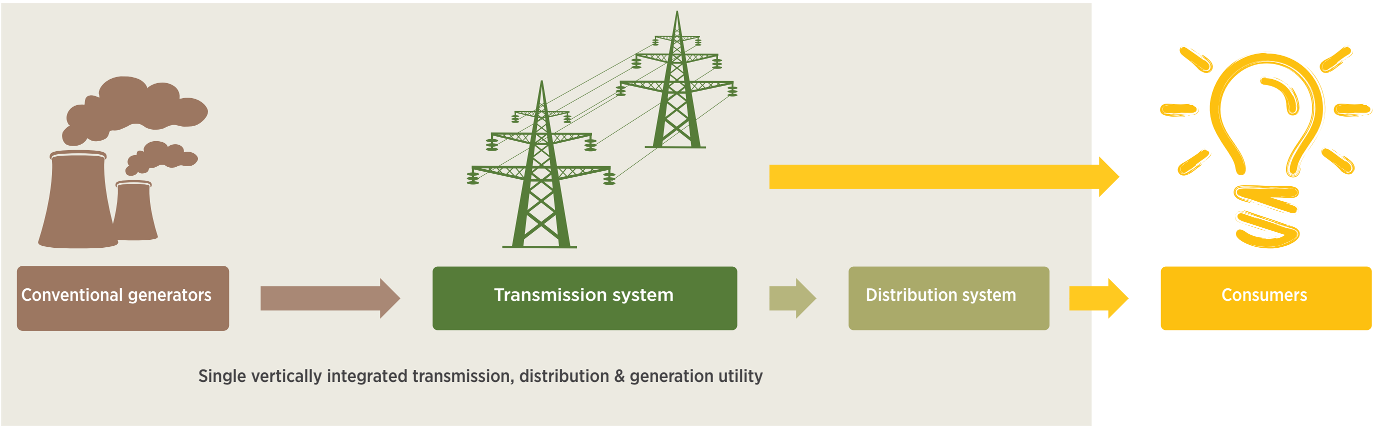
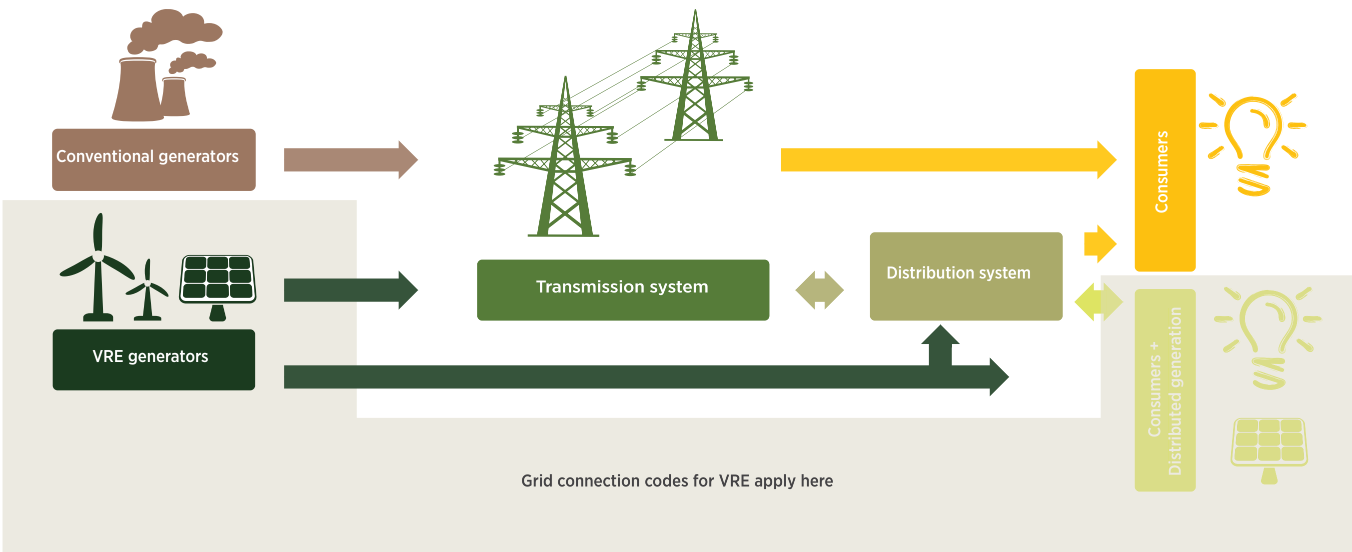


Figure 5: Unbundled system separating the operation of generation and grid.



From centralised to decentralised power systems

Figure 4 illustrates the change from a few large centralised thermal plants to numerous smaller renewable plants for Denmark. Denmark was a grid code pioneer. It developed some of the first interconnection requirements in the late 1980s to deal with increasing numbers of installed small wind and solar plants in the distribution system. During the 1990s these interconnection rules were harmonised into a grid code at the national level. By the early 2000s the system included both small renewable generators and larger offshore wind power plants.

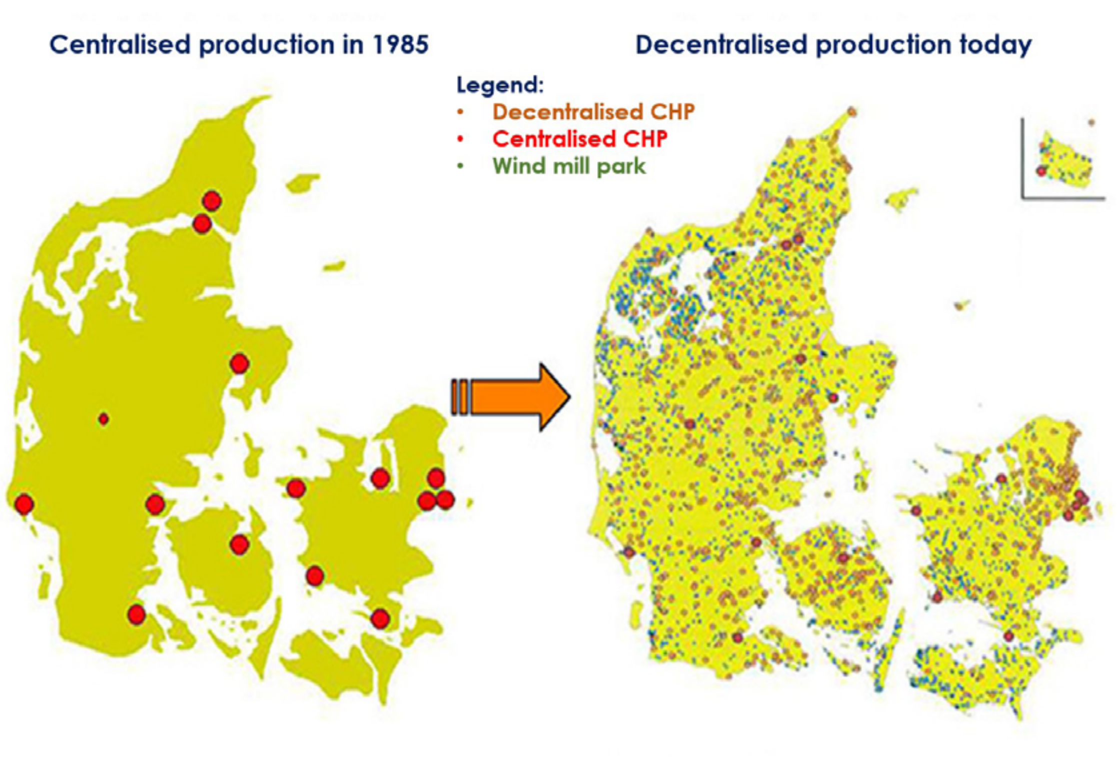


Figure 6: Comparison of Danish system in 1985 and 2006.

Source: (Energinet.dk, 2011)

In many countries, the rise of renewables has not coincided with unbundling. Some countries, such as Japan or small island states like Barbados, have retained vertically integrated utilities alongside private renewable generators which feed into the utility's grid. In these cases VRE grid codes are still required to provide technical regulations for the connection of renewables. Similarly, unbundled electricity systems may require grid codes for conventional generators in the absence of renewables.

TECHNICAL IMPACT OF VRE GENERATION

Variable renewable generators differ in several important ways from conventional generators like thermal or hydroelectric power stations.

Conventional generators typically either hold their active power output constant (baseload mode) or can vary their output based on demand (load following mode). The active power output of VRE generators depends on the weather. This variability can present challenges depending on the level of penetration and the characteristics of the conventional generators in the grid. Conventional generators must be able to compensate for the difference between variable renewable output and consumer demand fast enough not to affect frequency stability. Major, quick voltage changes due to variable feed-in can also disturb electricity consumers nearby and should be avoided.

Individual VRE generators (as opposed to aggregated solar or wind farms) are usually smaller than conventional generators. This is an advantage in that single VRE generator failure has less of a negative impact on the power system than the sudden disconnection of conventional generators. The small size of some VRE generators may mean there is no need to equip them with the functionality to provide certain system services. However, as the technology is evolving rapidly, these services may become more and more common among small VRE generators.

Conventional generators feed directly into the transmission network in a centralised manner. By contrast, small VRE generators, particularly rooftop solar PV, are often distributed across the power system and feed electricity in at low voltage levels. In the past only electricity consumers were connected at low voltage levels. If distributed PV feed-in exceeds the local electrical load, the voltage can exceed regulated limits. The reversed power flow on the low voltage power line may then exceed line or transformer capacity limits.

As well as being smaller and variable, renewable generators such as wind turbines and PV systems have different technical properties from conventional power stations. At first, inverter-connected wind and solar plants could not match the services provided by traditional power plants. However, technological innovation parallel with the development of grid codes has allowed VRE generators to be subject to requirements to help stabilise the network. For example, VRE generators can now provide reactive power for voltage control, active power reduction during congestion or over-frequency events, and network support during faults.

VRE generator response during faults

The requirement for Low Voltage Ride Through (LVRT) is an example illustrating the link between VRE impact and grid code development. During network faults such as short circuits, the voltage drops to some fraction of its normal value before the fault is cleared. Conventional generators stay connected to the grid during such disturbances and help minimise the spread of the voltage dip by feeding in high currents.

When they initially came to market, many VRE generators did not have this ability and simply disconnected when the voltage dropped below the lowest limit for undisturbed operation. Where there is a low share of VRE in the power system, this behaviour poses no problem to system stability. However, with a higher share of VRE, the simultaneous disconnection of several generators can cause a power loss that exceeds the primary operating reserves (see glossary). This then leads to a cascading failure in the power system. Many modern grid codes therefore require VRE generators to stay online for a certain period during voltage dips and also to contribute towards voltage recovery. VRE generator manufacturers have been able to develop units with LVRT capability.

New development incurs additional cost so it is usually first implemented in larger units. Scaling effects will make new technology more affordable so that it can be implemented in smaller units too.

PURPOSE AND FUNCTION

Technical requirements in grid codes are determined by the need to maintain the reliability, security and quality of the power supply and fulfil the objectives below.

- The electrical power needs of all consumers must be met reliably.
- Voltage and frequency must be maintained within set limits to avoid damaging equipment connected to the grid.
- The system must be able to recover quickly from system disturbances.
- At all times the system must operate without endangering the public or operating staff.

These basic needs are translated in the grid code into operational requirements demanded to all generators including VRE based on their technical impact described above. System operators make use of the services provided by power plants and other equipment to maintain system stability and safety.

A VRE grid code allows the network operator to provide clear rules and technical requirements for wind and solar plant operators when connecting to the country's electricity networks. Depending on the country, the network operator may use the fulfilment of the grid code as a precondition for connection to the network. The code can act as a legal requirement for connected generators, who may be prosecuted if the requirements are not fulfilled. As binding rules, grid codes help to ensure that generator owners and operators are treated fairly in terms of grid connection while ensuring system stability and reliability.

DIFFERENTIATION OF APPLICABILITY

Grid codes for VRE generators also have different domains of applicability.

VOLTAGE LEVEL

VRE grid codes may be drawn up differently for different voltage levels and/or depending on whether the VRE is connected to the transmission, distribution or offshore network. For example, grid code requirements for providing reactive power during faults often differ depending on the network level. Major faults occur at the transmission network level, so it makes sense for VRE generators connected to the transmission network to feed in reactive power during a fault in order to support the voltage. On the other hand, VRE generators connected to the distribution grid are often far from the source of the fault in electricity terms. It is thus less effective for them to provide reactive power support.

GENERATOR SIZE

The size of the VRE generator also affects applicability. VRE generators connected to the distribution grid are often small. This means it is less economical for them to meet stringent grid code requirements than it is for large VRE generators or VRE power plants with multiple generators connected to the transmission network. These cost considerations are then reflected in the VRE grid code requirements.

ENERGY SOURCE

Some VRE grid codes distinguish between the generator energy source. For example, Ireland has separate grid code rules to accommodate the behaviour of wind power plants. The Nordic Grid Code used in Scandinavia sets different requirements for conventional power plants distinguished by fuel type.

NETWORK OPERATOR

In a given country, different parts of the transmission or distribution network may be run by different network operators. Each network operator may have its own grid code or make additional requirements in addition to any national grid codes, based on local network conditions.

1.2 ROLE OF MODERN OPERATIONAL MEASURES AND TECHNOLOGY DEVELOPMENT FOR REGULATING VRE INTEGRATION

As well as enabling technologies like storage or demand side management technologies, VRE generation technologies are rapidly developing and facilitating new operational practices for power systems. Technology and operational practice improve the flexibility to operate power networks with a higher VRE share. Furthermore, these developments also require new rules to ensure that the electricity service to consumers continues to be secure, leading to the elaboration of grid codes, subsequent revision and updates. Regulations then pull through the best available technologies and also push new technology developments. This cycle, involving power system technology-operation-regulation, has turned the advanced technologies of a few years ago into now standard commercial technologies for grid integration.

A number of measures are available to facilitate up-to-date power systems operation with VRE generation. Storage through batteries or pumped storage facilities for example, is one option. Flexible loads (which can vary their electricity consumption according to VRE availability) are another. Two further options include controllable direct current (DC) converters and more flexible conventional generation with, for example, faster ramping rates and lower minimum loading levels. Similarly, better reactive power compensation and a Flexible Alternating Current Transmission System (FACTS) can improve power flow in the network. FACTS can prevent voltage violations caused by VRE feed-in or by the displacement of conventional generation in transmission networks. Other operational measures include better weather forecasting to predict VRE generation levels, improved markets for balancing power and dedicated dispatch centres for managing variable feed-in from VRE generators.

The requirements for these other network users is typically regulated in the other (non-VRE) connection codes. The operational aspects are typically covered in operating codes (see Figure 3). Many grid code documents contain provisions for different types of network users, including non-VRE power system actors. For example, in Great Britain the Grid Code applies to “all users of the National Electricity Transmission System, be they Generators, DC Converter owners, Suppliers or Non-Embedded Customers” (National Grid Electricity Transmission plc, 2014). Meanwhile, the Nordic Grid Code sets different rules for VRE and conventional generators.

As with VRE grid codes, the process of continually revising and updating regulations needs to be repeated for these corresponding system regulation documents (non-VRE grid codes and operating codes). One example of an evolving requirement of this kind for non-VRE system actors is the forthcoming introduction of a Demand Connection Code in the ENTSO-E Network Codes. This will govern demand side management in the European power system. Another example is the stricter requirements set in the operation codes within the ENTSO-E Network Codes, which specify requirements for conventional generator flexibility. (ENTSO-E, 2013)

The integration of VRE into power systems is not only about implementing VRE generator technical requirements in VRE grid codes. It is also about adopting measures that consider the whole energy system, from technology to operation, demand, markets and regulations (IRENA, 2015).

Regulations then pull through the best available technologies and also push new technology developments. This cycle, involving power system technology-operation-regulation, has turned the advanced technologies of a few years ago into now standard commercial technologies for grid integration.

1.3 RELATIONSHIP BETWEEN GRID CODES AND ENERGY POLICIES

An energy policy describes how a country addresses its energy needs, including converting and distributing energy from different sources. The governments of many countries have specific targets for renewable energy integration in their energy policies, which they support with incentives such as feed-in tariffs or quota systems (a mandatory renewable energy target). For example, Germany has a target in its Renewable Energy Act (EEG), amended in 2014, to meet 40%-45% of its electrical demand through renewables by 2025.

The role of VRE grid codes is to provide technical regulations for connecting VRE generators to the grid. This means VRE generators can contribute to power system stability and security, and thereby help fulfil the energy policy on renewables. The governmental body responsible for implementing a country's energy policy may mandate the creation of a VRE grid code. Alternatively, the VRE grid code may be drawn up separately from energy policy making. For example, in Australia the VRE grid code forms part of the National Electricity Rules established by law in the National Electricity (South Australia) Act 1996.

The technical requirements necessary in the grid code depend on the level of VRE in the power system. The grid code is thus related to a country's energy policy by the need to co-ordinate the technical requirements with the expected future VRE share. It is important that grid codes are written with the system security requirements for future planned VRE shares in mind. Similarly, energy policy regarding the VRE share should be formulated while bearing in mind existing and future grid code requirements. The network operator must plan ahead when drafting the grid code and anticipate future requirements in order to provide a stable regulatory environment for investment by VRE operators.

Example of lessons learnt from grid code practice: 'the 50.2 Hertz (Hz) problem'

The German '50.2 Hz problem' serves as an example of what can go wrong if grid code development is not co-ordinated with energy policy. A grid code requirement (VDE, 1994 / 2005) was set early on that was unsuitable for high VRE share, and unit behaviour had to be corrected through incentive programmes. The nominal frequency in Germany is 50 Hz. While PV levels were low in Germany, PV generators in the low voltage network were required to disconnect when the system frequency increased above 50.2 Hz. However] Germany's feed-in tariff encouraged PV installations, which grew so fast (see figure 5) that this disconnection behaviour posed a threat to system stability. With tens of gigawatts of PV suddenly disconnecting in the event of an over-frequency disturbance, the system could collapse. In 2011 and 2012, new requirements were introduced with a more gradual frequency cut-off, and policy makers had to provide incentives to retrofit older units (BMJV, 2012).

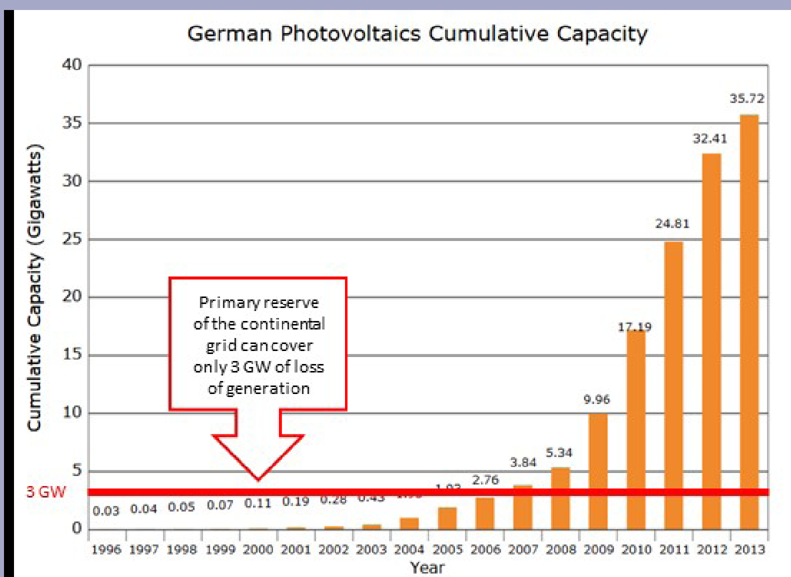


Figure 7: PV capacity in Germany, reaching 43% of peak load in 2014 and exceeding primary reserve capabilities from 2007

Based on data from German Federal Ministry for Economic Affairs and Energy (2015).

The 50.2 Hz problem mainly affected PV generators in Germany's low voltage network. In the medium voltage network there is also a legacy of inappropriate grid requirements relating to under-frequency – 'the 49.5Hz problem' (affecting primarily wind and cogeneration plants). This was also recently addressed by legislation - see next box. While 49.5 Hz is further from the nominal frequency of 50 Hz than 50.2 Hz, it is in principle more dangerous to disconnect large amounts of generation when the frequency drops. This is because it indicates there is already insufficient generation in the system to balance the load.

As an implementation detail of VRE support incentives, the concept of self-generation (similar or identical to self-consumption) has been established in some countries, such as Germany. This is an alternative or complementary support scheme for feed-in tariffs. There are two ways in which it relates to grid codes:

- It is often accompanied by a scheme to combine VRE generation with storage, which then allows different operation strategies with possible impact on grid operation and control.
- In addition to technical requirements for generators, some grid codes also specify metering configurations for consumers and/or generators; self-generation may require different metering configurations.

Metering is irrelevant to the technical discussion about VRE integration and therefore not covered by this report. No clear picture exists as yet of the best modes of operation for storage integration. The evolving market landscape and integration levels will need to be closely monitored to prevent undesired side-effects. Self-generation can also have an effect on average installed generator unit sizes and thereby influence when certain requirements become relevant for the different types of generators from a system perspective.

Example 2 of lesson learnt from grid code practice: 'the 49.5 Hz problem'

Another example of a learning experience is 'the 49.5 Hz problem' where inappropriate grid code settings contributed towards a partial blackout in November 2006 in continental Europe (UCTE, 2007). The medium voltage guideline in Germany at the time (VDEW, 1998) recommended that generators in the medium voltage network should disconnect if frequency fell below 49.5 Hz or increased above 50.5 Hz. Under normal circumstances the frequency is close to 50 Hz. During a major disturbance in the continental European grid on the night of 4 November 2006, frequency dropped to 49 Hz in one part of the network. This caused around 11 GW of wind and cogeneration plants in the medium voltage network to disconnect, resulting in further load shedding in the European network.

The medium voltage guidelines were altered in 2008 to require generators to stay connected down to 47.5 Hz (BDEW, 2008). However, by early 2015 around 27 GW of generators in the German network, particularly wind, cogeneration, biomass and small hydroelectric plants, were still programmed to disconnect if frequency fell below 49.5 Hz. The retrofit of many of these generators to disconnect only at lower frequencies was mandated by legislation in 2014 (BMJV, 2014).

Chapter 2

Grid Connection Code Development and Implementation

2.1 POWER SYSTEM CONTEXT

VRE grid codes can be developed for a grid operator's single control area, a country or even an entire region, comprising one or even several synchronously interconnected systems. VRE grid codes may thus vary in depth and technical content.

When developing a VRE grid code, a code applicable to another area, country or region cannot be transposed word for word since many requirements made for VRE generators depend on specific power system needs. The differences relevant to the grid code include:

- The size of the power system – peak load and geographical size -- which is relevant to the extent to which local VRE feed-in variations are smoothed when aggregated over a large area.
- Whether the power system is isolated or interconnected with other countries – interconnection allows the country to export its VRE generation peaks, and a larger interconnected system is less susceptible to frequency issues.
- Whether the grid typically has sufficient cable or line capacity reserves, which affects voltage rises along long feeders, for example.
- Existing and planned VRE capacities.
- How VRE resources are distributed geographically, which affects the extent to which VRE feed-in variations are balanced out when aggregated and the need for active power management of the generators.
- How VRE resources are distributed vertically in the power system, with VRE connected to transmission or distribution grids.
- The capabilities of the conventional generators that must cover the difference between VRE feed-in and electrical demand.
- The institutional framework i.e. level of unbundling between generation and transmission operators, regulation, etc.
- The historical aspects of VRE grid code development; in Germany and Denmark, for example, the grid code has evolved over time in parallel with the development of VRE plant manufacturer technology offerings to meet grid code requirements.
- State of the art – countries with newer VRE grid codes and a lower VRE share can already benefit from technology and lessons learnt from experience in pioneer countries, especially to avoid costly retrofitting later.

- Market situation – In countries looking to increase their VRE share, especially smaller nations, it may be necessary to consult closely with manufacturers, investors and operators to make sure that VRE grid code requirements are achievable.

The country-specific context for grid codes means expertise and local knowledge of the power system is needed when working them out. The grid codes of five countries, and the differences between them, are profiled in chapter 4.

Although each country may have specific grid code needs, many requirements can be harmonised between countries. Harmonisation allows countries to pool their resources in areas, like certification. This makes it easier for manufacturers to build equipment for several markets, which in turn keeps down costs for consumers. The relation between national and regional grid codes is discussed in chapter 5.

2.2 GRID CODE IMPACT ON STAKEHOLDERS

There are many stakeholders in the power system: owners and operators of generation assets, operators of transmission and distribution systems, regulators, manufacturers, installers and electricity consumers. The advantages and disadvantages of VRE grid codes for stakeholders in the power system are listed in Table 1. Not all of their needs coincide, so that the requirements in VRE grid codes often represent a trade-off between the interests of different stakeholders.

The role of each stakeholder and therefore the benefits and disadvantages of VRE grid codes may depend on the institutional framework in the respective country (such as the level of unbundling) as well as on the structure of the local energy market.

Table 1: Advantages and disadvantages of VRE grid codes for power system stakeholders

Stakeholder	Disadvantage of VRE grid code	Advantage of VRE grid code
Policy makers	Effort is required to align stakeholder interests and VRE energy targets	Supports operationalisation of renewable energy incentive policies while maintaining security of supply
Generator owners/operators	Fulfilment of VRE grid code requirements may require additional investment	Compared to ad hoc generator-specific requirements, provides level playing field and may reduce costs by allowing certification of particular manufacturer's models
Network operators and regulators (depending on country)	Resources are needed to draft, maintain and enforce VRE grid code	Maintenance of secure power supply; clear delineation of responsibilities regarding grid services
Manufacturers	Research and development to develop technology to fulfil VRE grid code; certification	Clear framework for grid integration, rather than diverse and therefore costly ad hoc arrangements
Consumers	All the VRE grid code costs described above might be passed on to the consumer in higher electricity prices and/or taxes	Security of supply; benefits of a higher VRE share

2.3 INTERNATIONAL STANDARDS

In the development and implementation of grid codes, other applicable technical and legal frameworks concerning the electrical energy system must be considered. Depending on their nature, these may either facilitate the use of a grid code or interfere with it. The most relevant frameworks are the regulations set by energy policy as discussed in section 1.3 and the technical requirements set by national and international standards (IRENA, 2013).

Generator technology, electrical equipment and other aspects of operating electrical power systems have been subject to national and international standardisation since public electricity supply structures started up in the 19th century. Therefore, many standards already exist that cover different aspects of modern VRE generator technology and operation. Requirements in standards relevant to VRE integration are driven by grid safety and stability needs. The technical committees in the standards organisations have the task of constantly analysing the existing situation and consulting with all stakeholders involved. International standards can only be published once a sufficient level of consensus on the technical situation concerned is reached. Standards are legally non-binding, but compliance with standards can be required by law.

ROLE OF INTERNATIONAL STANDARDS IN VRE INTEGRATION INTO POWER SYSTEMS

International standardisation processes are a valuable platform for countries and industrial actors to have discussions and exchange practices and experiences. Country experts should be encouraged and supported in engaging in international standard development. A wide range of international standards developed by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) are relevant to the integration of VRE into power systems. These technical standards cover many topics and have very different functions:

- Communication may be facilitated by defining technical terminology in a coherent way;
- Detailed specifications and requirements for technical equipment may be presented, ideally representing consensus among technical experts, with the goal of uniform engineering;
- Voltage quality and security of supply and its definitions are subject to international standards,
- Interconnection requirements for generators or other assets may be directly specified in international standards;
- Data transfer and broadcasting protocols may be standardised to ensure clarity of communication;
- Standard test methods describe standardised procedures that produce a test result and are often referenced in standard specifications as the preferred form of compliance testing;
- Standard practices or procedures are sets of instructions for operating technical equipment.

Standards may be directly applied in a country or modified to suit local conditions. Some standards produced by different standards bodies may be harmonised with each other. Most standards are very specific and give requirements in more detail than grid codes. They do not conflict with but complement grid code functionality. However, in certain cases, international standards for grid connection exist that closely resemble grid codes in scope and structure.

Annex B provides a list of international standards commonly used in relation to grid connection codes. The list is not exhaustive, and many more standards exist and are referenced from existing grid codes.

RELATIONSHIP BETWEEN INTERNATIONAL STANDARDS AND GRID CODES

Due to the varied scope, purpose and content of the individual standards, international standards and grid codes relate to each other in different ways:

- International standards can be referred to either fully or partly from within the grid code. For example, grid codes often specify power quality requirements by referring to the relevant standards rather than defining power quality explicitly.
- International standards can be used as a reference when writing a grid code and modified according to the specific needs of a country.
- International standards which govern the connection of VRE generators can in some cases be used in place of a grid code (see box below).

There are many advantages to using international standards within grid codes. Referring to international standards saves the investment of time and resources when writing grid code requirements from scratch. It provides some guarantee that the requirements have been tested and reviewed in other countries. It is also easier for manufacturers to conform to international standards than to comply with each different national set of rules. These cost savings can then be passed to the consumer.

Grid codes must be tailored to the specific requirements of individual countries. It is important to ensure that the international standards referred to make sense for that country. System operators responsible for grid codes also often take part in the development of standards. However, as more stakeholders are involved, revising international standards may prove to be more difficult than simply changing national regulations.

Countries usually strike a balance by writing their own grid codes and selectively referring to specific international standards where appropriate or in areas where there are no known considerations specific to that country. Since grid code harmonisation across countries is still desirable, standards concerning additional aspects of VRE grid connection are emerging and may shift the relationship between standards and grid codes in the coming years. This matter can be illustrated by considering IEEE 1547.

IEEE 1547

The IEEE developed its Standard for Interconnecting Distributed Resources with Electric Power Systems, or IEEE 1547, (IEEE, 2003) to provide a set of requirements for generators connected to the distribution grid. The US Energy Policy Act of 2005 (United States Department of Energy, 2005) establishes that "interconnection services shall be offered based upon the standards developed by the Institute of Electrical and Electronics Engineers: IEEE Standard 1547". This gives the standard the status of a US national distribution grid code. It has also been adopted as a US national standard by the American National Standards Institute (ANSI), the national standards organisation.

Rather like some European grid codes, it is in constant need of revision due to fast growth and VRE generation development. For example, it includes strict under- and over-frequency protection settings that require all distributed generators to disconnect at a certain threshold frequency (59.3 Hz/60.5 Hz). This could cause future problems similar to the German 50.2 Hz problem or trigger power oscillations in the overlaying transmission grid. Amendments to the standard have been made since its inception to keep up with ongoing development. Six complementary standards enhance the initial standard, some of which are still in the draft phase.

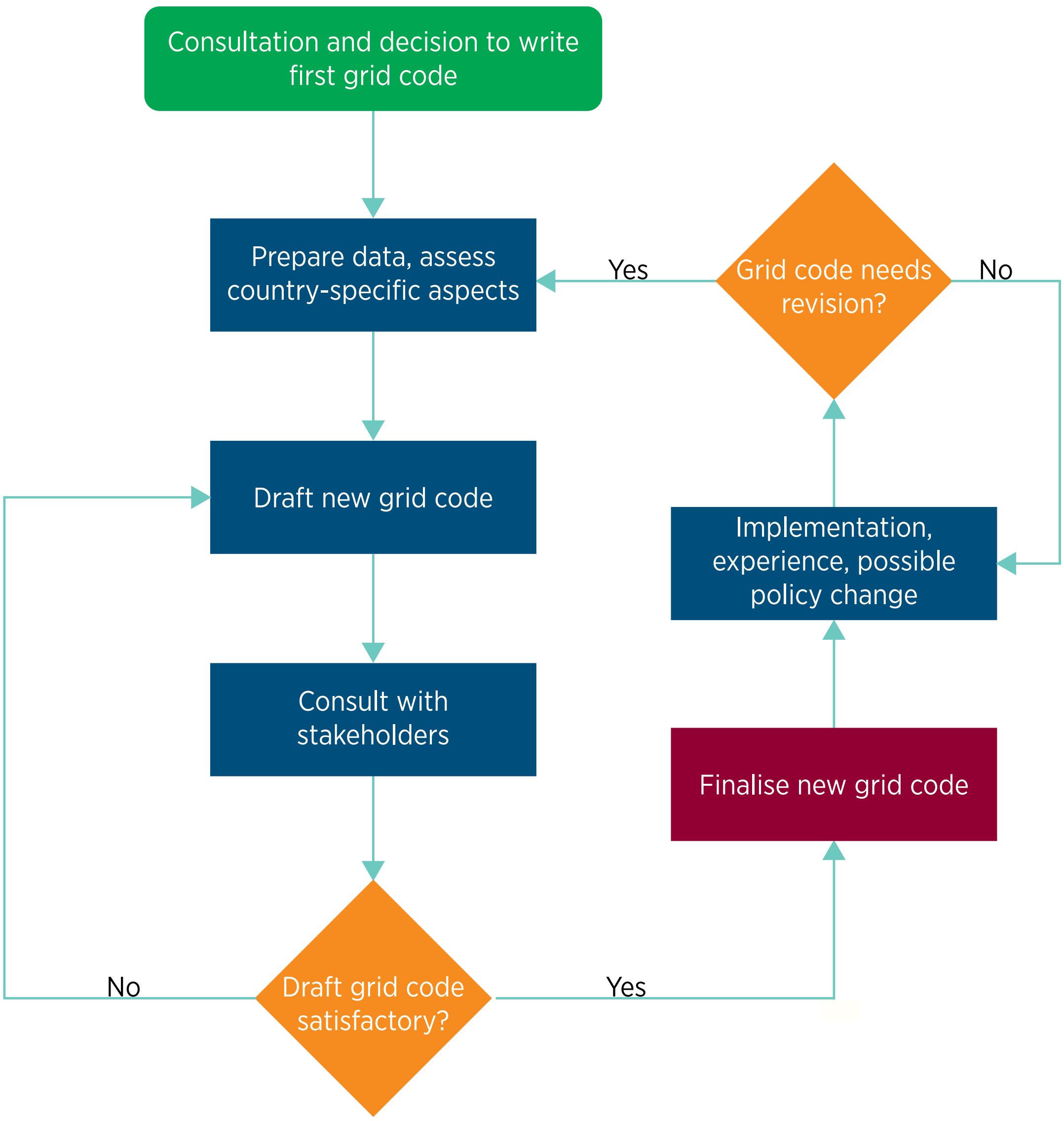
In Europe, the European Committee for Electrotechnical Standardization (CENELEC) is working towards governing the connection of distributed generation through international (European) standards similar to the US approach. Standard EN 50549 'Requirements for the connection of a generating plant to a distribution system' is being drafted and will replace standard EN 50438 'Requirements for micro-generating plants to be connected in parallel with public low voltage distribution networks' which is considerably less detailed than IEEE 1547.

IEEE 1547 has also been adopted by the IEC as IEC/IEEE PAS 63547 (IEEE, 2011). This is a recognised Public Available Specification, but not a fully applicable IEC standard and is rarely used outside the Americas.

2.4 GRID CODE DEVELOPMENT PROCESS

The process of developing and maintaining a grid code is outlined in Figure 8. A grid code must be sensitive to the developing needs of the power system so grid codes are often regularly revised on the basis of feedback and implementation and experience.

Figure 8: Grid code development



The roles of the different stakeholders are outlined in Table 2, followed by a detailed description of each step in the flow chart.

The stakeholder responsible for each stage of the grid code drafting, approval and revision depends on the institutional set-up in the individual country and the extent of unbundling in the power system. The typical roles for an unbundled system are laid out in Table 2.

Table 2: Roles of stakeholders in developing a grid code

Stakeholder	Role in grid code development
Policy makers	Take decision to require grid code on the basis of country's energy policy and consultation with other stakeholders. The grid code is typically mandated by law.
Regulator	Responsible for ensuring a grid code is written. Approves the finalised grid code.
Network operator	Responsible for preliminary studies, grid code draft, consulting other stakeholders, finalising grid code and then implementing, enforcing and revising grid code.
Manufacturers Generator owners, installers, manufacturers, consumers	Consulted during development of grid code.

Not all countries follow this division of responsibilities. In Australia, for example, the regulator writes and maintains the grid code while the network operator provides the regulator with technical assistance to draw up the requirements. In countries with no power system unbundling, the vertically integrated utility takes over the responsibilities of the network operator.

Each step in the grid code development flow chart is described below.

CONSULTATION AND DECISION TO WRITE FIRST GRID CODE

Policy makers are responsible for deciding whether a grid code is necessary. The decision to create a grid code depends upon existing regulation for grid users, the country's existing and future energy policy and consultation with other stakeholders in the power system. If third party generators are to feed power into the grid, a grid code is almost certainly necessary.

Policy makers usually mandate the development of a grid code in law. The regulator is then usually responsible for giving the mandate to the network operator to write the grid code and approving it. For a country's first grid code, additional effort and investment must be made by the network operator in the initial assessment of the power system and to assemble a team of power system and legal experts to draft the grid code. Subsequent grid code revisions can use existing knowledge and expertise.

PREPARE DATA, ASSESS COUNTRY-SPECIFIC ASPECTS

The desirable prerequisites for writing a grid code ideally include the elements below.

- expert knowledge of the country's power system, including all information about the existing electricity network and both the conventional and renewable generation fleet;
- a long-term plan for the power system infrastructure, including renewable energy targets up to 20 years in advance;
- an understanding of the challenges of VRE integration and the experience of grid codes in other countries;
- static and dynamic computer models of the power system so that simulations and stability studies can be conducted;
- simulations and stability studies to assess the benefit of different grid code requirements for the country's power system including the future VRE share;

- a cost-benefit analysis of the different grid code requirements balancing implementation costs with system reliability benefits and a higher VRE share;
- understanding of the country's legal system so that grid code requirements can be enforced;
- sufficient executives to write the grid code, enforce it, assess the implementation and then revise the grid code as necessary.

These data and studies allow the network operator to assess the requirements of the power system in a particular country and how they affect the grid code. For example, if the country has many long feeders on which the voltage is very sensitive to changes in power levels, stricter voltage control requirements may be needed.

DRAFT NEW GRID CODE

The grid code has to be drafted by the network operator in a clear and unambiguous fashion as mandated by the regulator. Boundaries may have to be set on the applicability of the grid code (e.g. whether it applies to the transmission or distribution system, which voltage levels and which generation technologies).

CONSULT WITH STAKEHOLDERS

Once a grid code has been drafted, the network operator should consult with other stakeholders in the power system to identify potential problems in grid code implementation. This includes, for instance, customers, existing generator owners and operators, potential future generator operators, regulators, manufacturers and installers. The grid code may need to be revised on the basis of their feedback. This consultation may also take place at the same time as the grid code is drafted.

FINALISE GRID CODE

Once the grid code has been drafted, final steps include applying to the regulator for approval for the grid code, setting the date from which it starts working and publishing the grid code. New or modified legislation to enforce it may be needed depending on the country.

IMPLEMENTATION, EXPERIENCE AND POSSIBLE POLICY CHANGES

After the grid code has been adopted it must be enforced. The network operator must validate whether generators comply with the grid code requirements and take action when it finds non-compliance. Grid code experience should be systematically gathered to provide feedback for the revision process. Changes to policy such as renewable support schemes or targets may also require revision of the grid code.

REVISE GRID CODE

A grid code is not generally written once and set in stone but revised every few years on the basis of experience of its implementation and the changing needs of the power system. In Denmark, for example, the first grid code for wind power plants was adopted in 1999. Major revisions followed in 2004, 2010 and 2015. The length of the revision cycle depends on the speed of VRE integration. If the grid code is revised too often, it may be difficult for installers and manufacturers to keep up with changing requirements. If the revision cycle is too slow, requirements may not be updated in time to help stabilise the power system.

Writing the grid code, verifying whether generators are complying, enforcing and revising the grid code all require investment, qualified staff and expertise. Countries may be able to pool resources in areas like generator testing and certification.

2.5 POLICY INSTRUMENTS TO FACILITATE FULFILMENT OF GRID CODE REQUIREMENTS

The fulfilment of grid code requirements may require additional investment by VRE and conventional generator operators and/or other stakeholders such as manufacturers. If these extra costs are too onerous for these stakeholders, new generators may not get built and VRE generation targets might not be reached. The fulfilment of grid codes can be facilitated in two ways through policy instruments. Firstly, stakeholders can be consulted in the process of drafting the rules. Secondly, support mechanisms can be provided to incentivise the fulfilment of advanced technical and operational capabilities.

The collection of stakeholder feedback (e.g. from manufacturers and operators) during the draft phase of both technical requirements and operational regulations is an important step. It ensures that requirements can be met without too much effort from the generators. The European Commission provides guidelines for stakeholder consultation, which can be used as a reference on how to implement this procedure (European Commission, 2014).

Policy makers and network operators or regulators can compensate the costs of advanced capabilities either through existing support mechanisms, such as feed-in tariffs, or by directly incentivising VRE equipment to meet VRE grid code requirements. The cost to generators of grid code compliance will arise anyway. However, providing a defined way for generator operators to recover this cost encourages investment, drives technology development and decreases costs in the long run.

Box: Incentives for grid code compliance

The System Services Bonus in the Germany's EEG is an example of direct subsidies for grid code fulfilment. In the 2009 update to the law, a bonus of EUR Cent 0.5per kilowatt-hour was introduced for wind turbines that fulfilled certain grid code requirements to maintain network stability. This was set out in the System Services Directive (Bundesministerium der Justiz und für Verbraucherschutz, 2009) (reactive power provision for voltage control, LVRT capability and active power reduction during over-frequency). The bonus was originally restricted to turbines coming into service before the end of 2013 but was extended by one year in EEG 2012. Retrofitting older turbines was also supported in EEG 2012.

2.6 GRID CONNECTION CODE ENFORCEMENT

The legal status and enforcement of grid codes vary from country to country depending on the institutional set-up of their power and legal system. In some countries, such as Australia, the grid code is both mandated and established in law. This means non-compliance with grid code requirements counts as a civil penalty, which can result in fines. In other countries, such as Germany, the development and publication of technical grid connection conditions by the network operators is mandated by law. However, the requirements are only a precondition for the network operator to connect the VRE unit.

In Germany, which has no single grid code, some of the main documents constituting the connection requirements for VRE generators are published as guidelines or 'application rules' by industry associations, which are not immediately binding. The system operators publish their own connection rules as required by law, which refer to the industry guidelines and provide further details where applicable. In addition, formal laws have been enacted that refer to a specific revision of the industry guidelines and application rules (occasionally also modifying them) and make them binding for any new VRE generation. More information on the structure of German grid code documents can be found in section 4.2.

In Barbados, where only one grid operator has responsibility for these matters, the law mandates that this public sector utility develops and publishes the connection rules – the grid code.

Mechanisms to verify compliance with grid connection codes by generators should be in place. Certification is a way to assure compliance with the grid code but it requires resources and technical capacity. Rather than checking that each individual VRE unit fulfils the grid code requirements of particular manufacturer models, network operators can mandate VRE grid code compliance through certification mechanisms. They can then stipulate in the grid code that the VRE operator only needs to present the certificate for its generator model to be able to connect to the grid. This can lower costs and encourage a higher VRE share. This is further explained in section 6.4.

...the requirements in VRE grid codes often represent a trade-off between the interests of different stakeholders.

Chapter 3

Requirements relevant to VRE integration

3.1 GENERAL NOTES ON TECHNICAL REQUIREMENTS

This chapter provides information on technical requirements to be considered in the development of a VRE grid code. Each of the requirements is briefly explained to provide the context to why and when it is needed.

More detailed descriptions and discussion of implementation can be found in annex A. In-depth presentation of physical phenomena or technical details are beyond the scope of this document.

IMPACT OF VRE SHARE ON TECHNICAL REQUIREMENTS

The requirements imposed on VRE generators depend on the existing and planned share of VRE in the generation pool of the system. When very few VRE generators were feeding electricity into the grid, the details of their behaviour were less important because their influence on grid stability could be easily managed. They were therefore allowed to behave in ways that were easier to operate and maintain using conventional practices. However, as the VRE share rises, VRE generators have to take over a growing number of duties from the conventional generators they replace. The role of VRE grid code requirements is to ensure that VRE generators acquire the technical capabilities to take over these duties. The code requests basic grid support services from new generators and is necessary for all voltage levels alike. System stabilisation requirements that were previously only demanded from conventional generators in the high voltage grids are now also relevant to VRE generators connected to the lower voltage levels. In countries with a very low VRE share, working out grid codes right from the start can ensure the desired grid support that helps smooth the transition towards a much higher VRE share.

TECHNOLOGICAL CONCERNS

VRE grid code requirements also arise from the very different generator concepts underlying VRE generation compared to conventional synchronous generators. Nearly all modern VRE generators are based on power electronic converters. These generator concepts differ significantly in terms of behaviour during network faults, emission of harmonic currents or inherent response to frequency changes, for instance. As a consequence, VRE grid codes need to codify rules previously taken for granted when synchronous machines were still the prevalent generator technology. On the other hand, power electronic devices allow the implementation of characteristics that cannot be provided using synchronous machines.

Requirements are usually specified as a minimum that needs to be met to obtain a grid connection. Many functions do not necessarily represent advanced technology, but have already been commercially available for several years. Other functions require more effort before they can be implemented. The different aspects related to the ease of implementation of given requirements are discussed in section 3.5.

RANGE OF FEATURES COVERED BY GRID CODE REQUIREMENTS

Requirements set out in VRE grid codes cover a variety of issues. This include, for example, basic power quality and system support during normal operation (contribution to voltage control and increasingly also frequency support). It includes specific behaviour during disturbances, such as short circuit current contribution and system protection requirements. Generator manufacturers may be encouraged to innovate in order to implement each requirement if technology does not inherently comply with needs.

VRE grid code technical connection rules often have to be implemented not only by individual generators, but require a system approach. Communication requirements ensure that a co-ordinated real-time system operation remains possible even where there is a high instantaneous VRE share. Simulation model requirements are imposed by grid codes or by system operators to ensure that system planning and design remains feasible in continuously changing systems. Setting the parameters of

3.2 STUDIES REQUIRED AND RECOMMENDED TO DETERMINE PARAMETERS

many requirements means investigating the needs of the power system. Requirements must consider the capabilities of available generator systems in order not to obstruct VRE adoption. The following studies are needed:

- load flow studies to investigate the necessary reactive power capabilities of generators; consulting manufacturers need to identify the capabilities of existing products and evaluate potential cost of extended capabilities;
- static and dynamic short circuit studies for evaluating protection and LVRT requirements;
- ramping study on reserve requirements and gradient limitations, ideally including frequency stability study.

This list only includes studies relating to VRE grid code parameter creation and should be added to studies to be conducted for system planning and operation purposes.

3.3 OVERVIEW OF TECHNICAL REQUIREMENTS

VOLTAGE AND FREQUENCY OPERATION RANGES

Customers connected to electrical power systems are provided with alternating voltage of standardised magnitude and frequency. Operation ranges describe how far voltages in reality may deviate from this ideal. This can never be attained exactly due to the physical properties of the grid, its generators and loads. All equipment is therefore able to operate within some tolerance around the nominal values. However, larger deviations can cause permanent damage or equipment breakdown.

A typical voltage tolerance band for unrestricted generator operation is ±10% of the nominal value. The frequency tolerance is usually much smaller, around ±2% in large interconnected systems. In smaller systems or island systems, slightly larger frequency bands are usually required because frequency control is harder to handle. Outside the given tolerances, generators must remain operational for a minimum period or may disconnect immediately depending on the magnitude of the disturbance. The time intervals specified provide a safety margin for the system operator to respond to disturbances. As will be discussed in the country-case studies, experience indicates that disconnection requirements as narrow as 49.5 Hz and 50.2 Hz in a 50 Hz system, for example, should be avoided.

The key considerations are listed as:

- all generators must be fully functional within a specified voltage band around the nominal value - often ±10%;
- required frequency withstand tolerances are around ±2% in large interconnected systems and exceed this in smaller systems.

POWER QUALITY

Beyond magnitude and frequency, voltage and current deviations from nominal values also occur in terms of waveform distortions and short-term fluctuations. These deviations are classified according to their characteristics and can be measured with appropriate methods. They are referred to as aspects of power quality and are specific to a given location in the electricity network in a given time interval.

All generators have an inherent influence on at least some aspect of power quality in their vicinity. This influence depends on the technology of the generator system and therefore differs between conventional generators and typical VRE generators. VRE grid codes codify rules corresponding to several aspects of generator influence, aiming to guarantee compliance with certain voltage quality levels for all equipment and connected users.

The key considerations are:

- Power quality covers a range of phenomena related to voltage waveform and magnitude. All generators influence power quality;
- Power quality requirements specify limits for emitting voltage disturbances and current for each asset connected to the grid;
- All generators including VRE at any penetration level must comply with similar limits to ensure suitable voltage quality for power system users.

REACTIVE POWER CAPABILITY FOR VOLTAGE CONTROL

Power system operators maintain the voltages in the system within their desired ranges primarily by managing the contribution of reactive power from generators. Conventional generators in large power plants provide a wide reactive power capability range available for this purpose. However, due to the different generator technology, VRE generators do not inherently provide similar capability ranges. Instead, desired reactive power capability ranges must be explicitly considered when a VRE generator is being designed, and therefore may have a significant impact on generator cost.

Improved VRE generator reactive power capability helps to raise the level of VRE penetration in two ways. Firstly, reactive power can be used in the distribution system to reduce the voltage rise prompted by the distributed generator active power injection. More installed capacity can then be connected before network equipment must be upgraded, thus helping reduce costs. Secondly, as VRE generation displaces conventional power plants, the reactive power demands of the transmission system still need to be fulfilled. Wide reactive power capability ranges equal to at least the largest VRE power plants help reduce conventional must-run capacity for voltage control needs.

The key considerations are listed as:

- Wide reactive power capability and controllability of VRE generators generally allows higher VRE penetration;
- In the distribution system, wide reactive power capability can reduce grid reinforcement needs caused by VRE integration;

- In the transmission system, wide VRE power plant reactive power capability helps reduce conventional must-run capacity.

FREQUENCY SUPPORT

Frequency is a global parameter of a synchronous alternating current (AC) power system. It is kept within a small range around the nominal value by maintaining the balance of load and generation at the transmission system level. As long as sufficient generation capacity is available to cover the load, the most significant peril to frequency stability is a sudden change in the power balance. Imbalances of this kind can be caused by the disconnection of a large load or power plant due to a fault or by very quick changes in the power output of several VRE generators within an entire area. Operators maintain power reserves in order to mitigate frequency changes and continuously balance the load within their control area.

As denoted by the term VRE, such generators depend on the fluctuating availability of primary energy for their power injection into the system. From the perspective of the power plant dispatcher in a system with VRE priority feed-in, the aggregate of both load and VRE generation must be balanced via the conventional generation park. Tuning the capabilities of VRE generators to the requirements of power balancing during disturbances relieves the stress on conventional capacity that must be retained for frequency control. It thus encourages higher VRE penetration, while maintaining the same levels of frequency stability.

The desired response of generators to frequency disturbances depends on the type of imbalance. Too high a frequency indicates a surplus of generation, in which case the power injected into the grid should be reduced. Too low a frequency indicates a lack of generation so that power injection should be increased in order to avoid load shedding.

The key considerations are:

- VRE generation is not particularly well suited to providing frequency control. However, support measures for frequency disturbances are available through VRE;
- During episodes of over-frequency, VRE generators should first gradually reduce their power output while remaining connected to the grid. They should only disconnect at a specified threshold with sufficient margin to the nominal frequency. Such requirements are already part of most VRE grid codes;
- To provide reserve power during episodes of under-frequency, a VRE plant would need to be capable of reduced output operation mode. This involves spilling free primary energy and is still under discussion in most countries due to related issues concerning the power market and priority feed-in.

FAULT BEHAVIOUR

Faults in a power system are events, such as line interruptions or short circuits on transformers, cables or overhead lines. Short circuits cause very high currents, which lead to physical damage to equipment within a very short time. They are also used for reliable fault detection. Grid assets are protected by relays that detect such currents and switch off the asset. The high currents during the short circuits are provided by the generators in the system and also help limit the voltage impact of the fault. To prevent damage, the faulty elements have to be disconnected sufficiently quickly. The generators themselves must remain connected during the fault so that the proper fault detection is not compromised. Generators also need to remain connected afterwards so that the power balance in the system is maintained after the fault is cleared.

Requirements imposed on VRE generation in terms of fault behaviour therefore resemble the requirements of conventional generators. The code provides exact descriptions of conditions when generators must remain connected to the grid after the initial voltage dip that correlates with every short circuit. The desired feature for injecting supporting current for fault detection is also demanded of

VRE generation above a minimum size or voltage level. However, it is always subject to the constraints of the underlying technology. Conventional generators are inherently capable of providing high short circuit currents. However, the provision of these higher than nominal currents from VRE generators must be considered in the generator design. It has a direct and significant impact on generator costs.

The key considerations are:

- With increasing VRE power plant size and VRE penetration, VRE generators need to remain connected for a limited period during grid faults in order not to endanger the power balance;
- Due to technology constraints, VRE generators are not capable of injecting similar levels of current required for fault detection already provided by conventional generators. Nevertheless, imposing manageable minimum requirements, such as a current contribution limited to the nominal current, supports the system needs.

ACTIVE POWER GRADIENT LIMITATIONS

When there is a high share of VRE and priority feed-in, the power injection ramps caused by fluctuating primary energy become a relevant factor concerning power reserves allocated by system operators. The conventional power plants providing reserves often only dispose of limited ramping capabilities. This means VRE ramps that greatly exceed the usual demand ramps also change the magnitude of necessary ramping capacity. In contrast to the frequency support requirement described above, the concern here is not the response to disturbances but the probability that such disturbances will be caused by VRE fluctuations.

The maximum VRE power ramp can be adapted to the ramping capability limits of the conventional operating reserve by imposing ramping restrictions on VRE. Whether such ramping restrictions are easy to implement depends on the cause of the power ramp. An increase in primary power can be mitigated relatively easily by limiting the power injection ramp. However, a quick unforeseen decrease in primary power can only be limited by employing some kind of reserve that kicks in when the power injection drops too fast. Besides primary energy fluctuations, ramps can also result from a number of events. These include VRE plant start-up and shutdowns in normal operation and during or after fault incidents, wind park shutdown during high winds, and activation or deactivation of reduced output operation modes. Limiting the resulting ramps in these situations is already common practice.

To avoid increased power reserves due to VRE power ramps, modified market structures can act as an alternative approach to active power gradient limitations in VRE grid codes. VRE generators could then contribute to frequency services and provide reserves, where possible, instead of increasing the needs for reserves.

The key considerations are:

- The variable power injection of the aggregated VRE generation can cause ramping requirements that increase the required reserve capacities needed to avoid power imbalance;
- Imposing ramping limits on VRE in these cases helps limit the necessary ramping reserves and thereby contributes to system efficiency;
- The effort required to implement VRE power gradient limitations depends on the cause of the power gradient.

SIMULATION MODEL

Simulating sets of possible scenarios plays an important role in power system planning and operation. Grid operators often use computer simulations to predict the behaviour of their grid, especially the transient behaviour in fault incidents or extreme events. These simulations depend on reasonably complete and accurate models of the grid and the generator systems dominating its behaviour. Grid operators depend on plant operators to provide models for their power plants. Generator owners are thus often required by the system operator to hand in simulation models in a specified format before they are allowed to connect their unit to the grid.

Correlating with system impact, simulation models are in the first instance required for the largest power plants (including VRE). They are also required for smaller plants connected to lower voltage levels with an increasing share of distributed generation. To maintain the accuracy of the operator's general system models, rules on plant models in grid codes cover model functionality, accuracy and validation procedures. The models are usually developed and provided by the plant manufacturers.

The key considerations are listed below.

- Simulations are used by system operators to analyse and predict the behaviour of their system. These simulations depend on sufficiently complete and accurate power plant models for all significant types of generation;
- When the VRE share or plant size becomes significant, grid codes start mandating simulation models for these plants. Models have to be provided in a specified format and need to fulfil requirements on functionality and accuracy.

ACTIVE POWER MANAGEMENT

One key task of power system operation is to balance load and generation by allocating the corresponding resources in sufficient quantity on the power markets. The final power plant dispatch also takes grid stability requirements and transmission capacity limits into account. To effectively conduct this task and manage the active power resources in systems containing a rising share of VRE generation, VRE generator need to be able to access active power management.

Since VRE generator power injection primarily depends on the availability of wind and solar radiation, its manageability differs greatly from that of conventional generator systems. Once they start feeding power into the grid, these can usually vary their operation between their rated power output and a minimum operating level. VRE generators, however, depend on external conditions for available output power and have almost no minimum operating level. VRE generation is made accessible to power plant dispatch mechanisms by communicating maximum output levels; the generators then limit their power output accordingly when sufficient resources for higher output are available.

VRE generator active power management is desirable even in power markets with VRE priority dispatch. This is because they can then contribute to grid congestion management and stability. When a significant VRE share is reached, VRE generators thus need to provide active power management capabilities.

The key considerations are listed below:

- Power system operators need access to power plant dispatch for managing grid stability and congestion;
- VRE generators can access active power management if temporary power output limits are imposed. VRE generator systems thus need to integrate the facility to accept and adhere to these limits;
- VRE generators are required to provide active power management capabilities even in power markets/regulations with VRE priority dispatch.

COMMUNICATION

Power system operation requires communication in several ways. Real-time measurement data transmission is necessary to assess the system state. Control commands such as the desired states of switching equipment or generator set points must be communicated to the corresponding actors. Communication must therefore extend to all significant generation assets, and security of communication must be provided in order not to endanger system operation through communication failures.

As VRE generation grows in significance, VRE power plants need communication interfaces to implement the advanced features required by the grid code. Active power management and power reduction for reserve provision purposes is especially relevant. However, gradient limitations and reactive power controllability all also necessitate dynamic control access by the system operator. While communication methods used in the past have been specific to vendor, modern power systems converge on communication channels based on international standards. One example is the ISO/IEC 27000 series on information security management systems. Another is the IEC 61850 series on communication networks and systems in substations. A third is the IEC 62351 series on power systems management and associated information exchange - data and communications security.

The key considerations are listed below:

- When VRE penetration reaches a moderate level, VRE generators need communication interfaces to implement functions such as reactive power control and the different methods to influence active power management;
- Communication methods should be based on international standards to avoid vendor dependency, encourage competition and ensure cost efficiency.

PROTECTION

Reliable operation of a power system always depends on the careful implementation of strategies that mitigate the impact of faults and other disturbances. The most reliable power systems count with several layers of protection, and are able to identify and isolate faults quickly and with minimal impact on the remaining system. Generators must possess a certain level of resilience against faults in the grid, but also need to be equipped with protective devices that can disconnect the generator before permanent damage is taken.

Grid codes not only specify when generators need to remain connected to the grid during faults (see the section about fault behaviour above), but also stipulate requirements of how the protection system at the point of connection shall be designed and which settings are to be used. Generator owners are normally responsible for additional measures that prevent damage to the equipment. All settings should be compatible with the requirements concerning fault behaviour.

The key considerations are listed below:

- For consistent behaviour, generator protection measures at the point of connection must follow common schemes with common settings in the grid codes. This applies to all generation at all levels, including VRE;
- Effective prevention of generator damage is within the responsibility of the generator owner. All protection settings must be compatible with the requirements related to fault behaviour.

3.4 OUTLOOK FOR VRE GRID CODE REQUIREMENTS

With the VRE share rising to an unprecedented level in more and more countries, VRE grid codes are subject to further development and are acquiring new rules. The paragraphs below provide a brief overview of technical requirements currently under discussion in the countries with the most VRE. Only new requirements are listed, as opposed to adjustments strengthening existing requirements.

CONTRIBUTION OF INERTIA OR SYNTHETIC INERTIA

The fastest power reserves employed to balance sudden changes in load or generation usually need a few seconds before the reserve power is activated. It is essential that this delay be tuned to the maximum rate of frequency change expected in the system to limit the magnitude of any frequency excursion. The maximum rate of change of frequency (RoCoF) primarily depends on the inertia of the rotating masses of the synchronous generators connected to the system and the magnitude of the power imbalance.

Regardless of their power rating, converter-based VRE generators do not provide inertia. At a high instantaneous penetration of VRE generation, the remaining conventional generation from synchronous generators may not provide enough inertia. The rate of change of frequency might then be too high for the system to remain within the designated frequency limits in the case of the highest expected imbalance. This is a factor causing must-run conventional capacity in the system.

Advanced control methods at VRE generator control systems can allow the implementation of inertia known as synthetic inertia from VRE generation. Such implementation entails significant design effort and may also necessitate additional hardware components. Agreeing on rules for future VRE grid codes thus involves considerable research, development and discussion. Once achieved, such rules can help raise the limits of achievable VRE penetration.

BLACK-START CAPABILITY

System operators of large transmission and isolated power systems must be able to re-start the system after it has gone down. Although this ability is hardly ever exercised in the largest transmission systems due to their high reliability, both the necessary kind of generation plants and the strategic energisation plans must be ready for use. The ability to start a generation plant without any externally provided electricity is called black-start capability. Such power plants are the centre from which the step-by-step process of system energisation sets off. Classic providers of black-start capability are particular hydropower plants and individual thermal plants with additional storage.

VRE generator units alone cannot easily acquire black-start capability, although their primary power supply may be plentifully available at a time when this function may be needed. The main obstacle is the ability to perform effective frequency control and voltage control in an islanded system, implying for example a quick match of generation to the connected load. This would need to work both for a single unit as well as for a set of different units while enlarging the island and possibly connecting with other islands. Any method for implementing black-start capability with VRE generation would usually include a conventional generator or storage system capable of fast balancing. Hence, including black-start in a VRE grid code would always apply at the plant level and not at the generator unit level.

DAMPING POWER SYSTEM OSCILLATIONS

The connection of rotating machines to an electrical power system forms a system capable of electromechanical oscillations. If there is insufficient damping, such oscillations pose a threat to system stability and can lead to equipment damage. Damping measures are therefore implemented in the control systems of large conventional power plants.

Studies are being conducted to investigate whether or how the increasing share of VRE generation changes the oscillatory behaviour of large transmission systems. Depending on the outcome of this research, VRE generators may be required to contribute to the damping of certain kinds of oscillations. This could include lower order and inter-area oscillations caused by synchronous generators swinging against each other. Some means of damping oscillations may even be easier to fulfil for a converter than for a synchronous generator.

3.5 IMPLEMENTATION

Depending on the type of VRE generation, technical requirements imposed on generators can be easy to implement or require significant effort. The subsection below therefore lists the most important technologies and provides a brief discussion on the ease of implementation of different technical requirements. Since requirements are also of different importance from a power system and VRE share perspective, another subsection follows that provides a prioritisation of requirements within the power system context. The last subsection in this chapter lists the most important types of studies that help determine the technical parameters of requirements when drafting or revising a VRE grid code.

EASE OF IMPLEMENTATION

The ease of implementing VRE grid code requirements depends on many factors. This includes the type of generator, manufacturer and time the manufacturer has had to develop technologies that comply with the grid code requirements. Some requirements can be implemented simply by updating the software. Others may need new hardware as well as software.

In Table 3 the ease of implementation by the dominant generator technologies are discussed. The following five generator categories are covered:

1. Classical synchronous machines used in conventional power plants. This is included for comparison purposes only because it is not used by many VRE generators.
2. PV units connected to the grid by a DC-to-AC converter.
3. Wind turbines with rotating generators of variable speed connected to the grid by a converter with full power rating of the generator[1] ('full converter').
4. Wind turbines with double-fed induction generators (DFIG), a technology with converters of lower power rating than the generator itself.
5. Wind turbines with squirrel-cage induction generators (SCIG), a cheap generator technology without converters and with reduced capabilities, mostly used in older or smaller wind turbines.

Table 3: Ease of implementing grid code requirements for different VRE technologies.

Requirement	Synchronous machine	PV converter	Wind turbine with full converter	Wind turbine with DFIG	Wind turbine with SCIG
Power quality: harmonics (see section 3.3)	No issues	Depends on design, and needs integrated filters	Depends on design, and needs integrated filters	Depends on design, and needs integrated filters	No issues
Power quality: flicker (see section 3.3)	No issues	No issues	Mitigation via control	Mitigation via control	Poor power quality
Reactive power capability (see section 3.3)	Wide capability range	Converter can provide wide range of reactive power if sufficiently dimensioned	Converter can provide wide range of reactive power if sufficiently dimensioned	Limited capability, controlled by rotor side converter; may require extra equipment	reactive power not controllable, needs additional compensation equipment
Frequency support: reduction at over-frequency (see section 3.3), active power management (see section 3.3)	Full control	Full control, maximum is subject to irradiation	Full control, maximum is subject to wind conditions	Full control, maximum is subject to wind conditions	Limited controllability via pitch and/or rotor resistor
LVRT, including current contribution (see section 3.3)	Can be achieved within converter, which can supply current during fault	Can be achieved within converter, which can supply current during fault	Can be achieved within converter, which can supply current during fault	Can be achieved within generator and converter control	Requires significant additional equipment

1 This includes electrically excited synchronous machines as well as permanent magnet generator systems (PMGS) and induction machines. As all functionality is provided through the converter, the type of generator machine does not affect the properties relating to the grid.

Requirement	Synchronous machine	PV converter	Wind turbine with full converter	Wind turbine with DFIG	Wind turbine with SCIG
Inertia (see section 3.4)	No issues	Complex implementation of synthetic inertia, may require storage	Complex implementation of synthetic inertia	Complex implementation of synthetic inertia	No issues

VRE power plant operators can sometimes meet grid code requirements by introducing equipment at the power plant or transformer level rather than for each individual generator unit. For example, to meet LVRT requirements, plant operators have used capacitors or power electronics to feed in reactive power at the connection point during the fault (see section 6.3 - Retrofitting old generators).

PRIORITISING REQUIREMENTS IN A POWER SYSTEM

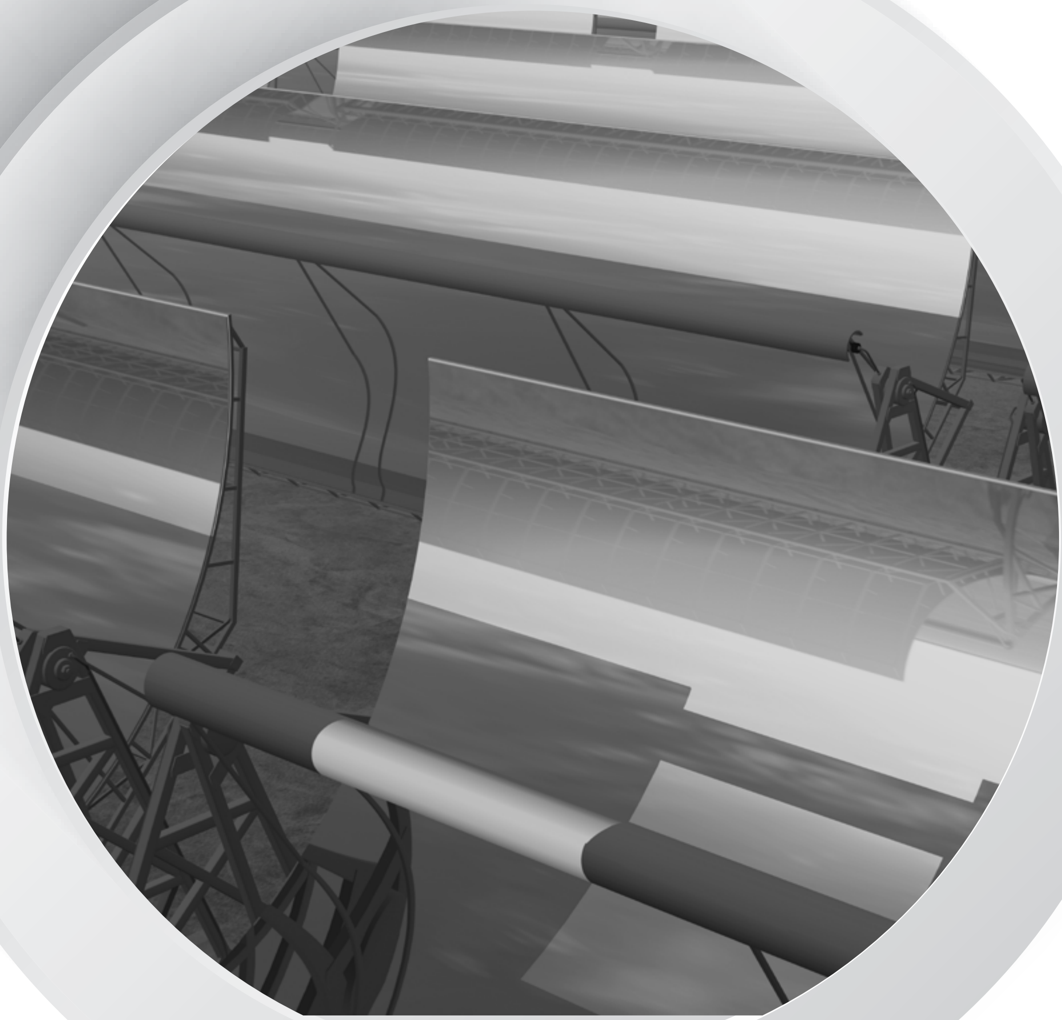
In a changing power system, the main driver for new requirements for VRE generators is the highest instantaneous share to be expected in operation. This parameter is referred to as 'VRE share' in the following prioritisation table (Table 4). In this scale, 'low VRE share' approximately refers to single digit percentages and 'exclusive use of VRE' means percentages close to 100%. The table is indicative; there are no exact boundaries between the intermediate VRE share levels. All listed requirements remain necessary when the next VRE share level is reached.

Table 4: Prioritising technical requirements according to VRE share.

Power system context	Technical requirements
Always needed	• protection, • power quality, • power reduction during over-frequency
Low VRE share	• communication • adjustable reactive power • constraining active power (active power management)
Higher VRE share	• LVRT including current contribution • simulation models
Very high VRE share	• active power gradient limitation • reduced output operation mode for reserve provision • synthetic inertia
Exclusive use of VRE	• stand-alone frequency control • full integration into general frequency control scheme • stand-alone voltage control • full integration into general voltage control scheme

Existing and forecast island systems are thus far aiming for a very high VRE share at most. Exclusive VRE use in a power system of significant size is accompanied by significant challenges at present. Great efforts from a policy and technology perspective will thus be required to make this feasible in future in situations where it can be efficient.

Chapter 4



Case Studies

This section provides a brief review of five international examples of grid codes. It covers a wide spectrum of geographical locations, size, industrialisation, VRE integration level and electrical interconnection with other countries.

4.1 CASE STUDY OVERVIEW

Australia, Barbados, Germany, Ireland and the Philippines are selected in order to include systems of very different characteristics according to the criteria listed above. A brief overview of the cases selected is given in Table 5.

Table 5: Overview of power systems selected as case studies.

	Germany (ENTSO-E, n.d.) (ENTSO-E, 2014)	**Ireland** (EirGrid Plc., 2015a) (EirGrid Plc and SONI, 2012) (ENTSO-E, 2014)	**Australia** (National Electricity Market) (AEMO, n.d.) (AEMO, 2015)	**Barbados** (BLPC, 2015b)	**Philippines** (Philippines Department of Energy, 2014)
Population (million)	80.6	4.6	23.1	0.28	98.4
Area [km²]	357,114	70,273	7,692,024	430	300,000
Interconnected with other countries?	Strong interconnection	AC interconnection with Northern Ireland on synchronously independent island of Ireland. The island has two HVDCs* with Great Britain	Several synchronously independent zones	Synchronously independent island	Several synchronously independent zones
Peak load [MW]	81,738 (2014)	4,613 (2014)	33,100 (2014)	152 (2014)	11,822 (2014)
Minimum load [MW]	36,709 (2014)	1,664 (2014)	14,900 (2014)	82 (2014)	-

	Germany (ENTSO-E, n.d.) (ENTSO-E, 2014)	**Ireland** (EirGrid Plc., 2015a) (EirGrid Plc and SONI, 2012) (ENTSO-E, 2014)	**Australia** (National Electricity Market) (AEMO, n.d.) (AEMO, 2015)	**Barbados** (BLPC, 2015b)	**Philippines** (Philippines Department of Energy, 2014)
Total conventional generating capacity [MW]	108,000 (2014)	7,405 (dispatchable 2014)	48,000 (2014)	239	17,500 (2014)
Wind [MW]	38,000 (12/2014)	2138 (2014)	3,600 (01/2015)	0 (03/2015)	283 (2014)
PV [MW]	38,000 (12/2014)	0 (2014)	3,440 (01/2015)	7.6 (03/2015)	23 (2014)
VRE capacity versus minimum load [%]	207%	128%	47%	9.30%	-
Yearly load [Terawatt-hour (TWh) p.a]	505 (2014)	29 (2014)	188 (2014)	0.968	77 (2014)
VRE share of annual load [%] (International Energy Agency, 2010)	19.56%	15.50%	7.50%	1.30%	0.22% (2014)
VRE connected to distribution or transmission level?	Both	Both	Wind to both, PV mostly to distribution	Distribution	-

Each of the case studies to follow includes a brief power system overview, highlighting recent development of VRE share and future targets. The grid code landscape is described, referring to requirements specific to the given system(s), legal status, revision process and future outlook. References are provided as sources for further information.

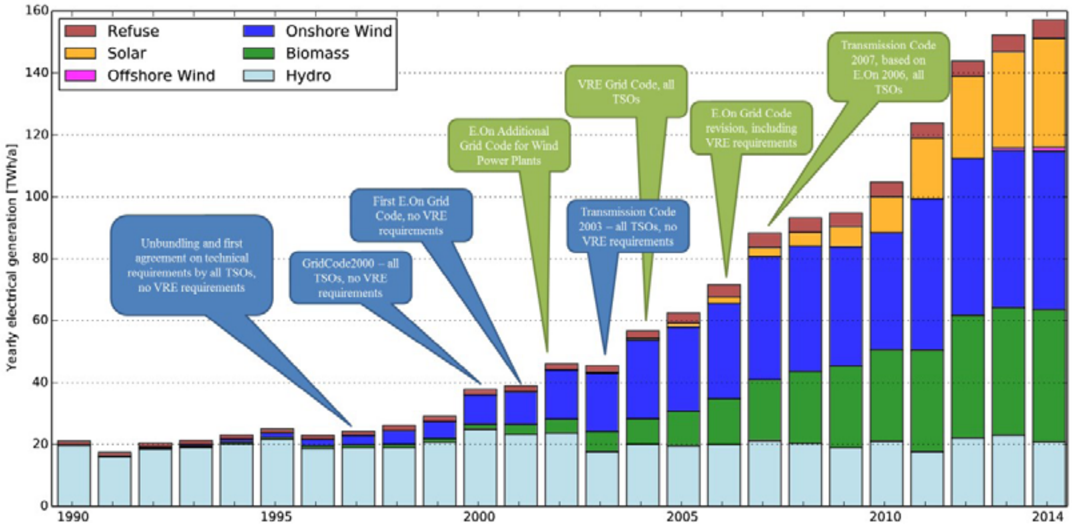
4.2 GERMANY

POWER SYSTEM OVERVIEW

Germany is a large, industrialised country with the largest electricity consumption in Europe, amounting to 522 TWh in 2014. The load varies between around 40 gigawatts (GW) and 80 GW. Germany introduced priority feed-in for renewables and a basic feed-in tariff in 1991. The resulting growth in renewables, as shown in Figure 9, covered nearly 30% of Germany's electricity consumption from renewable energy by 2014. About half of this came from VRE and the rest from hydroelectric power and biomass. Conventional generation is largely based on coal with a diminishing share of nuclear and gas-fired generation. The grid was originally built for large, central generation. German renewable energy targets remain high, and the plan is to source 40%-45% of electricity production from renewables by 2025.

Germany's power system is large and very well interconnected within the European continental grid. It consists of a transmission grid with rated voltages of 220 kilovolts (kV) and 380 kV, a sub-transmission level at 110 kV and distribution grids from 0.4-30 kV. The transmission grid is historically divided into four zones, each controlled by a separate TSO. The underlying grids belong to a multitude of different owners. Wind power plants today mostly feed into the medium voltage grid but newer, large installations are also sometimes connected directly to the high voltage level (110 kV and above). The bulk of solar PV generation is provided by rooftop installations connected to the low voltage grid.

Figure 9: Renewable electricity generation and grid code development in Germany since 1990 (based on statistics from AG Energiebilanzen e.V.)



GRID CODE LANDSCAPE

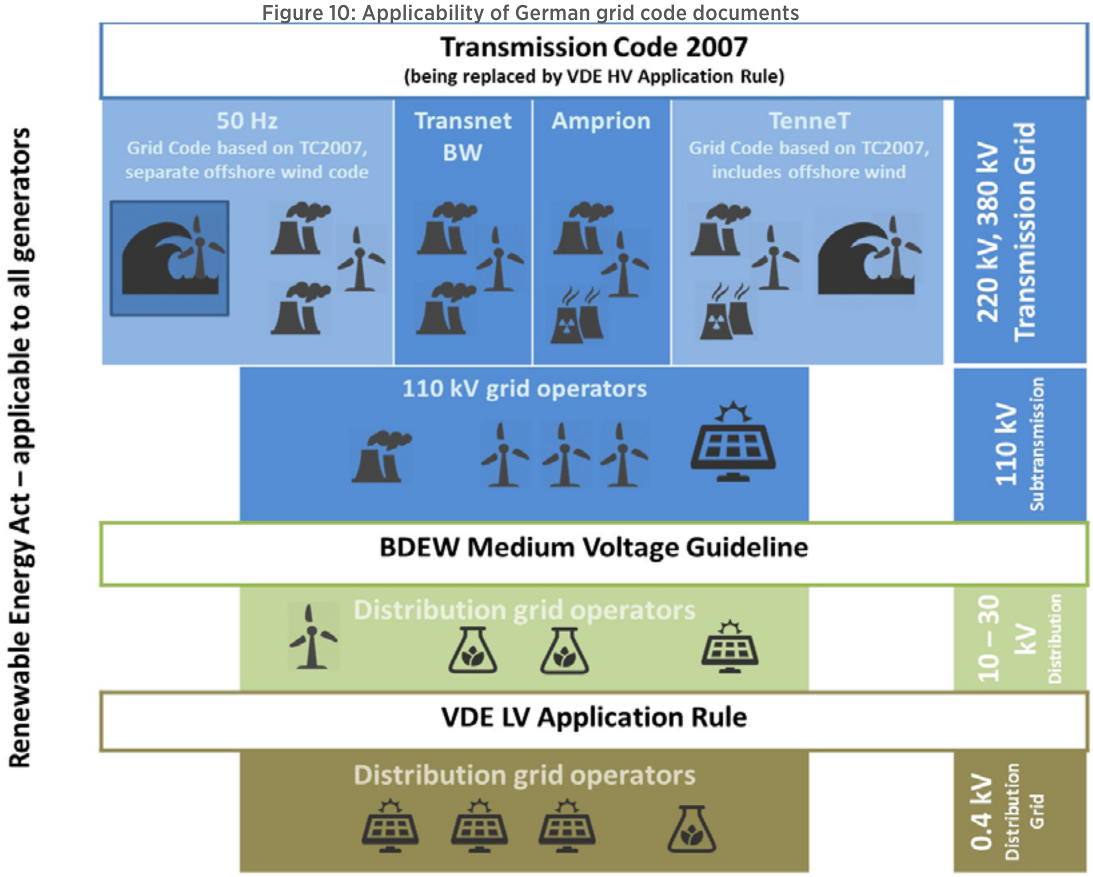
Germany is also a pioneer in the development of grid code requirements for VRE generators. E.ON, one of the grid operators at the time (now taken over by TenneT TSO), published the first requirements for VRE generators in 2001 as the bulk of German wind generation was installed in the E.ON grid.

The Transmission Code 2007 (TC 2007) governs transmission grid operation in Germany. Several different documents govern the connection at voltage levels of 1-100 kV as well as at below 1 kV as shown in Figure 10.

The TC 2007 allows grid operators to specify further requirements in some places. For example, it has three different reactive power requirements for generators of which the grid operator can choose one or more depending on the local grid conditions. Each TSO has thus either developed its own grid code based on the TC 2007 or uses the TC 2007 directly.

The TC 2007 distinguishes between synchronous and inverter-based generators. Inverter-based generators such as those in VRE plants, have to fulfil slightly less demanding requirements. Generally, in other countries, VRE generators have to fulfil the same requirements as conventional generation. Germany was among the first countries to introduce LVRT requirements for wind turbines following investigations in the early 2000s. These showed that the concentration of most all German wind power on the North Sea coast could mean the loss of a high amount of generation during fault incidents and thus endanger grid security. Reactive power control is also required, particularly in the additional offshore wind grid codes that two of the four TSOs have developed. VRE generators may also not trip at frequency deviations. Since Germany has a major level of interconnection, quick reaction requirements to support frequency stability like synthetic inertia are currently not a concern in German grid codes.

Figure 10: Applicability of German grid code documents



Technical requirements for generators connected to the medium voltage level are specified in the medium voltage guideline published by the German Association of Electricity and Water Suppliers (BDEW) in 2008. (BDEW, 2008). This requires all generators, including those from VRE, to provide reactive power for voltage control and includes detailed LVRT requirements. Large sections of the technical requirements in the medium voltage guideline were directly taken from TC 2007. The guideline also governs grid access and connection issues. It is notable in setting very strict limits on the allowed voltage rise caused by generators. Voltage may not be increased by more than 2% at any point in the grid compared to the same grid without any new generators.

Since August 2011, generator connection to the low voltage grid (0.4 kV) is governed by an application rule (VDE, 2011) published by the German Association for Electrical, Electronic & Information Technologies (VDE). It focuses only on technical requirements for generators connected to the low voltage grid, including those from VRE plants. All other low voltage grid specifications are dealt with in other documents. Considering this limited scope, its requirements are very strict. This is due to the high amount of solar PV connected to the low voltage grid in Germany. Many of the technical requirements are directly derived from TC 2007 but modified to suit the needs of the low voltage grid. The application rule sets different rules for generators depending on rated power. It contains detailed requirements on voltage quality and control (by means of controlled reactive power behaviour) as well as installation compliance with several national and international standards, LVRT is not required for generators connected to the low voltage grid (mainly solar PV generators). Generators may not trip during over-frequencies but are required to reduce output slowly instead. This addition was made in 2012, with old units being retrofitted (BMJV, 2012). Previously, PV units were required to disconnect at 50.2 Hz by a VDE standard. This led to the '50.2 Hz Problem' described in section 1. For further information on the retrofit programme see section 6.3: Retrofitting old generators.

GRID CODE LEGAL STATUS AND REVISION PROCESS

The EEG is a law that sets rules for VRE generation applicable to all generators. The 2014 revision (BMJV, 2014b) of the law currently applies but it first came into force in 2000 and was preceded by the 1991 Electricity Feed-In Act (Stromeinspeisungsgesetz). It has thus been in existence longer than any grid code. Most rules specified in the EEG concern national renewable energy targets, legal requirements and feed-in tariffs. Some also specify technical requirements that are either included or referenced in the grid code documents.

The EEG demands electrical energy from renewable generation as priority feed-in. This means conventional generators must reduce their power output to provide grid access for renewables if required. The grid operator is allowed to curtail renewable generation only if grid congestion cannot be resolved by reducing conventional generation or if conventional generation cannot be reduced further.

German grid codes are constantly revised and updated as conditions in the grid evolve. Generators are required to meet the requirements of the grid codes in force at the time their grid connection is accepted by the system operator. The certification of generators for grid code compliance unique to Germany and is required for new generators and new VRE power plants (see section 6.4: Generator compliance).

Once the importance of VRE generators providing system support had been recognised, some grid code requirements were incentivised retrospectively. See section 6.3: Retrofitting old generators).

GRID CODE OUTLOOK

The sections on generator connection in TC 2007 are currently applicable to all voltage levels above 50 kV, which includes the 110 kV sub-transmission level. Due to the changing role of the 110 kV grid, a VDE application rule very similar in structure to the low voltage application rule (VDE, 2015) is under development which will be applicable to 110 kV only. The draft is mainly a restructured TC 2007 with some specific rules for the 110 kV level, including more detailed LVRT requirements. The new regulation retains the same degree of freedom for the individual Distribution System Operators (DSOs) as TC 2007. The four German TSOs do not own a 110 kV system. A revision of the low voltage application rule is also under discussion, and LVRT requirements may be included in the near future (TU Delft, 2014). The medium voltage guideline has recently been updated. All German grid code documents will eventually have to be revised to comply with the ENTSO-E Network Codes, which are due to be signed into EU law (see section 5 - Relationship between regional and national grid codes). This will mostly be a revision of the document structure - not the requirements themselves.

KEY CONSIDERATIONS

- Germany has been able to reach significant levels of VRE penetration, which it aims to further increase. The existing measures in the grid codes to maintain a safe and secure power system thus seem adequate for current conditions. In this context, Germany benefits from its strongly interconnected position within the central continental European synchronous area.
- Experience has shown that the requirements stipulated in the grid codes did not always sufficiently anticipate the speed of the change in German power system. The retrofit of VRE generators to remedy the 50.2 Hz and 49.5 Hz problems is progressing. However, a more far-sighted grid code development would probably have mitigated the underlying operative concerns more efficiently.

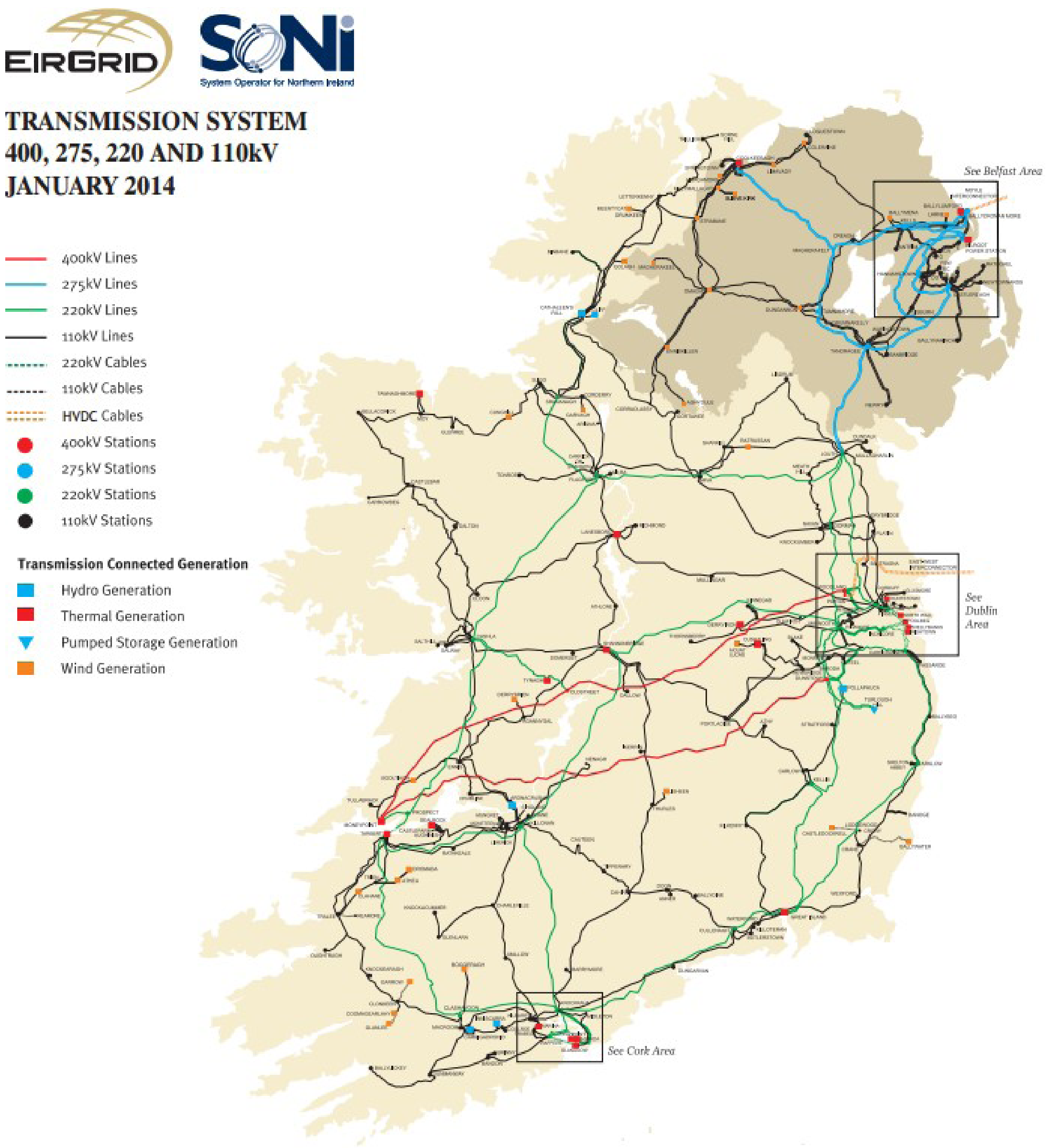
4.3 IRELAND

POWER SYSTEM OVERVIEW

Ireland is interconnected with Northern Ireland - see Figure 11. The two TSOs EirGrid (for Ireland) and the Systems Operator for Northern Ireland (SONI) collaborate closely on wind and grid code integration.

The island of Ireland must regulate its own frequency (unlike Germany, whose frequency is coupled to its neighbours via AC transmission lines). Two HVDC subsea lines connect the island of Ireland to Great Britain with installed capacity of 500 MW each. However, the Moyle Interconnector is limited to 250 MW capacity, restricting total transfer capacity to Great Britain to 750 MW. The island of Ireland has an electrical load which varies between 2,400 MW and 6,300 MW and by 2014 had a wind capacity of around 2,900 MW. This gives Ireland one of the highest VRE penetration levels for an individual multi-gigawatt synchronous system. As a result of this high wind generation, Ireland has been at the forefront of a great deal of research. This has considered the consequences of high VRE penetration and how grid codes can help the power system accommodate hours of high VRE feed-in.

Figure 11: Transmission grid of the island of Ireland. Ireland is shaded lighter than Northern Ireland.



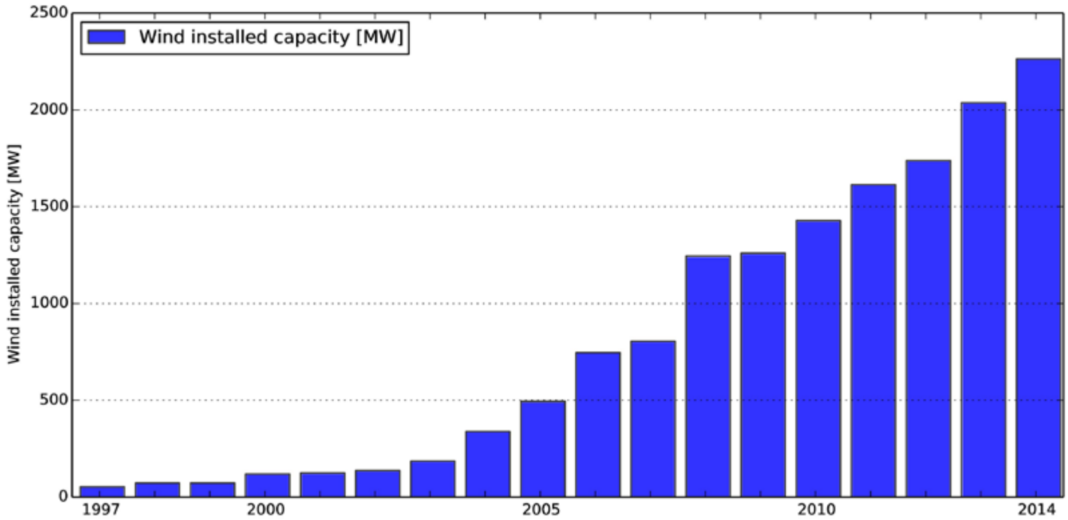
Source: EirGrid and SONI, reproduced with permission from EirGrid)

Non-synchronous power sources like VRE generators and HVDC lines have no inherent inertia to stabilise short-term frequency changes. The TSOs EirGrid and SONI thus currently employ a limit of 50% instantaneous System Non-Synchronous Penetration (SNSP) of the load and are investigating ways of raising this limit to 75% (EirGrid Plc., n.d.). Of particular concern is frequency stability after either the loss of the largest synchronous generator or severe network faults. Mitigation measures, such as revised rate of change of frequency requirements and the provision of synthetic inertia by wind turbines, should mean that the 75% SNSP target is achievable by 2020 (Creighton et al., 2013).

The remainder of this section now focuses on Ireland, excluding Northern Ireland. VRE generation in Ireland is dominated by wind. The development of installed wind capacity in Ireland is shown in Figure 12.

The country's transmission system is defined as power lines at voltages of 110 kV and above[2]. It has voltages of 110 kV, 220 kV and 400 kV in its transmission network. Everything below this is defined as the distribution system. Ireland's wind capacity of around 2.2 GW is split. Around 60% is connected to the distribution system and 40% to the transmission system. Ireland has set a target to generate 40% of its electricity from renewables by 2020. In 2014 it generated just over 20% from renewables.

Figure 12: Wind capacity in Ireland since 1997



Based on statistics from the Irish Wind Energy Association)

GRID CODE LANDSCAPE

The TSO EirGrid writes and maintains the grid code for the transmission system (grid code) (EirGrid Plc, 2013) while the DSO ESB Network writes and maintains the grid code for the distribution system (distribution code) (ESB, 2015). The grid code and distribution code review panels consist of representatives from the following stakeholder groups - as set out in the constitutions for each code review panel: the DSO and TSO, energy regulator the Commission for Energy Regulation, conventional generators, renewable generators, demand side units, suppliers, major demand customers, the market operator SEMO, interconnectors and the transmission asset owner ESBN. The Electro Technical Council of Ireland sits on the Distribution Code Review Panel. For the grid code there is also a Joint Grid Code Review Panel with representatives from the stakeholder groups in Northern Ireland. This panel discussed the Ireland grid code and the SONI grid code. The individual members of EirGrid's Grid Code Review Panel are listed online[3].

Both the transmission and distribution codes existed for other generators and consumers before specific provisions for wind generators were introduced. There are currently no grid code provisions specifically for solar generators although consideration is being given to defining standards for PV.

2 Some 110 kV lines in the Dublin area are operated by the distribution system operator and thus not part of the transmission grid.

3 See www.eirgrid.com/operations/gridcode/membersconstitution/.

The first grid code clauses for wind farm power stations were approved by the regulator the Commission for Energy Regulation in July 2004. Because of concerns about system stability, the regulator had introduced a moratorium on new wind plant grid connection in December 2003 until suitable grid code standards and connection processes were developed. The process of developing the first wind grid code clauses for Ireland is documented in (Fagan et al., 2005).

Subsequent revisions to the grid code and distribution code have further clarified the technical requirements for wind farm power stations particularly in the more advanced areas. These include, for instance, active power control, ramp rates, voltage control and the provision of dynamic models.

Because it has high level of VRE penetration for a single synchronous system, the current Version 5.0 of the EirGrid grid code (EirGrid Plc, 2013) is at the cutting edge in terms of requirements to support the power system. Advanced measures include:

- The EirGrid grid code was one of the first to require detailed dynamic computer models of VRE generators (applying at the moment to wind farm power stations greater than 5 MW) to simulate transient behaviour during faults with high VRE feed-in.
- Both Ireland and the UK are noteworthy in requiring all generators to remain connected during high rates of change of frequency of 'up to and including 0.5 Hz per second.' Such high rate of change of frequency can occur in island systems due to the loss of a large synchronous generator or an interconnector. It is important that this does not trip anti-islanding protection in the VRE generators. A body of work is under way in Ireland and Northern Ireland to change this requirement to 1 Hz per second as one of the measures to enable an increase in SNSP to 75%.
- All wind farm power stations greater than 5 MW must be capable of receiving set points for active power, frequency response and voltage regulation from the system operator. This is particularly important given that Ireland currently limits SNSP to 50% and may need to curtail wind generators to maintain this limit.
- The wind farm power station must be able to control the ramp rate of its active power output over a range of 1-100% of its nominal capacity per minute.
- The LVRT requirement is quite strict: all wind farm power stations greater than 5 MW must remain connected if the voltage at the connection point drops to 0.15 per unit for 625 milliseconds (a longer time than required by other grid codes).

GRID CODE LEGAL STATUS AND REVISION PROCESS

The grid code and its revision process are overseen by the regulator the Commission for Energy Regulation.

The grid code provides for a grid code review panel, which has a well-defined procedure for inviting suggested modifications to the grid code. Once the panel has reviewed the revisions to the grid code, they must be approved by the Commission for Energy Regulation.

The modifications are published online in a transparent manner. Most of the modifications are accompanied with explanatory texts to provide the background for the changes[4]. Revised clauses in the EirGrid grid code typically apply to all generators, including both existing and future plants. A modification requiring more detailed harmonic limits on generators and users of the transmission system is an example of how this issue was explicitly dealt with. In the modification proposal[5], the working group "agreed that limits will not be applied to existing connections unless they were previously advised or they are subject to a material modification," so the modification is only applied to new plant or upon refurbishment of old plant.

4 See www.eirgrid.com/operations/gridcode/modifications/
5 See www.eirgrid.com/media/MPID264Proposal.pdf

GRID CODE OUTLOOK

The island of Ireland's VRE targets mean that it may have up to 5,000 MW of wind capacity by 2020. To avoid curtailing VRE generation, the TSOs would like to raise the limit on SNSP from 50% to 75%. One of the main stumbling blocks to increasing the SNSP limit is the high rate of change of frequency that is expected during faults with higher shares of wind in the system (Creighton et al., 2013). Wind farms must stay connected during these events to avoid cascading failures. Current modifications to the grid code in this respect are under consideration.

The grid code will also have to be harmonised to comply with the ENTSO-E Network Codes. The ENTSO-E Network Codes allow special provisions for the island systems of Ireland and Great Britain. This includes frequency range, LVRT and frequency control requirements that differ from the continental grid (ENTSO-E, 2013).

KEY CONSIDERATIONS

- The island of Ireland has its own synchronous zone and one of the highest shares of VRE generation (primarily wind) of any power system of comparable size. VRE penetration is projected to rise further. To manage safe, secure and efficient power system operation in this situation, the Irish grid codes are among the most demanding in terms of generator requirements;
- Compared to other grid codes, the Irish requirements request more demanding frequency withstand capability, LVRT envelopes and advanced integration functions such as configurable ramp rate limitations. Ireland has avoided large retrofitting programmes by setting grid code requirements early enough. It also achieved this by setting a moratorium on wind power grid connection in 2003 until suitable grid code standards and requirements were developed.

4.4 AUSTRALIA

POWER SYSTEM OVERVIEW

The Australian power system is composed of several different synchronously independent areas (see Figure 13), the largest of which falls within the National Electricity Market (NEM). This covers the South and East of Australia, including the states of Queensland, New South Wales, Victoria, South Australia and Tasmania (connected to the rest via a subsea HVDC link). The transmission networks in each state covered by the NEM are managed by different network operators. Western Australian and Northern Territory are not part of the NEM. This is managed and overseen by the Australian Energy Market Operator (AEMO).

The NEM power system, stretching along the coastline of Australia, is unusually long and linear compared to meshed systems in Europe and North America. It is the world's longest interconnected system, stretching over 5,000 kilometres. The long transmission lines in the system lead to oscillatory stability problems not seen in other smaller, meshed systems. Meanwhile the linearity means that faults can lead to islanding (when parts of the network lose synchronism with the rest). The grid can be weak in remote parts of the network where wind power plants are connected. The grid code thus has special provisions to negotiate site-specific requirements (such as enhanced voltage control capability).

The peak load is 33 GW, the majority of which is concentrated in (in descending order) in New South Wales (Sydney), Victoria (Melbourne) and Queensland (Brisbane). At the start of 2015 wind generation capacity was 3.6 GW and PV capacity was around 3.4 GW. VRE contributed around 7.5% to overall electricity generation. The remaining electricity generation is dominated by coal, with some gas, hydroelectricity and biomass.

In 2009 Australia introduced a mandatory renewable energy target to cover at least 20% of electricity generation from renewable sources by 2020, calculated at 41 Terawatt-hour per annum (TWh/a) at the time. In June 2015 Australia reduced this target for renewable generation to 33 TWh/a to reflect reduced electricity consumption.

Figure 13: Transmission Lines (AC and DC) in Australia

Source: Orr and Allan, n.d.*

GRID CODE LANDSCAPE

The VRE interconnection in the NEM is controlled by the Australian National Electricity Rules (AEMC, 2014), which govern aspects of the power system ranging from market rules to transmission system planning. It applies to all voltage levels, including the distribution and transmission network. Version 66 of the National Electricity Rules, available since 1 December 2014, provides the technical rules relevant to VRE generators, in particular schedule 5.2 – 'Conditions for Connection of Generators'.

The first version of the National Electricity Rules was established under the National Electricity Act of 1996 (South Australian Legislation, 1996). The National Electricity Rules came into force when the NEM started up in 1998. The National Electricity Rules were initially based loosely on the grid code of Great Britain's National Grid but has many features unique to Australia.

The National Electricity Rules are published by the Australian Market Energy Commission (AEMC), which is also the custodian for changes to the grid code. The AEMO assists the AEMC on technical requirements.

The National Electricity Rules are notable for making no strong distinction between VRE generators and generators with conventional fuel sources. The rules attempt as far as possible to make the same technical requirements of all generators with the exception of sometimes distinguishing between asynchronous and synchronous generating units.

The National Electricity Rules are unusual in mandating both minimum access standards which every generator must meet and stricter automatic access standards. If a generator meets the automatic access standards, connection cannot be refused on technical grounds. The VRE operator and network service provider can also negotiate levels of compliance between these minimum and maximum requirements depending on the power system needs of the particular site. Site-specific requirements are important in Australia given that the grid can be weak in remoter areas where wind resources are good.

For example, the reactive power requirement for the automatic access standard is for the generator to supply reactive power equal to 39.5% of its active power rating. This capability is necessary at all levels of voltage and active power output. The minimum access standard states "no capability is required to supply or absorb" reactive power. Similarly, lower and upper ranges are set for power quality, frequency response, LVRT and communications.

The National Electricity Rules are also unusual in requiring on-site testing of fulfilment of grid code requirements unless the AEMO makes a specific waiver. For power plants consisting of multiple wind turbines, several turbines will be tested individually before focussing on the collective behaviour at the point of common coupling. Typically LVRT is not tested since these tests are intrusive. However, live monitoring can help validate plant behaviour during accidental faults due to lightning strikes, for example. Guidance for compliance testing can be found in templates published by the AEMC (AEMC, 2012), which were under review in 2015 (AEMC, 2015).

Australia has relatively strict requirements for the provision of computer simulation models, which are described in the Generating System Model Guidelines (AEMO, 2008). The National Electricity Rules require both static and transient stability models containing functional block diagrams of the generator and all control systems to do with frequency and voltage control. The models must be accurate both for each generating unit (measured at its terminals) and for the whole power plant. These models must be provided as unencrypted source code in the format of one of the major power system analysis tools. The clauses on test compliance are classified in the National Electricity Rules as "civil penalty provision[s] under the National Electricity (South Australia) Regulations". Validation is important in Australia, mostly through on-site test, because of the specific needs of some sites. Generic manufacturer models may not capture the behaviour of particular units.

The regulators in some states within the NEM have additional generator requirements based on their specific needs, which are provided in separate grid codes. An example is South Australia, the state with the highest installed wind capacity. It is subject to additional mandatory requirements for generators (ESCOSA, 2010), particularly with respect to LVRT and reactive power capability. These are very similar to the automatic access standards. Similarly Tasmania has additional requirements on frequency control given it is an island system.

GRID CODE LEGAL STATUS AND REVISION PROCESS

The National Electricity Rules have the force of law and are developed under the National Electricity Law (South Australian Legislation, 1996). This allows fines to be imposed for non-compliance.

The revision process is overseen by the AEMC, which invites changes and manages the National Electricity Rules updates.

GRID CODE OUTLOOK

The rising share of inverter-based generation in the NEM is causing some concern. There is a view that in future there may not be enough inertia in the system to counteract frequency changes resulting from sudden power imbalances. This may require adjustment to grid code requirements although the present low VRE share creates no problems in this respect.

Additional grid code clauses are also being considered for storage technology since storage can act as both a consumer and generator of electricity. Hence it does not fit neatly into the existing framework.

KEY CONSIDERATIONS

- Australia's electricity system consists of several independent synchronous zones, the largest of which is somewhat unusual in its topology. Its North-South path is extremely long but the transverse is quite narrow. It is thus unable to provide the same level of contingency/reliability reserves as the meshed systems in most of Europe or in the US.
- The Australian grid code reflects this structure by allowing customised connection requirements adapted to the designated point of connection and stringent requirements for on-site performance testing and simulation models.

4.5 BARBADOS

POWER SYSTEM OVERVIEW

Barbados is a densely populated island in the Lesser Antilles in the Eastern Caribbean. The island has no interconnection with other islands and must therefore regulate its own frequency. In 2014 the peak electrical load was 152 MW, which occurs at 12-2pm (BLPC, 2015b). Almost all the island's electricity comes from imported petroleum products with the rest coming from small PV and wind installations. The electricity network and conventional power stations are operated by the vertically integrated utility Barbados Light and Power Company.

The government's Renewable Energy Rider support scheme (BLPC, 2014b) has been widely adopted. It provides credit for wind and solar-generated electricity provided that the generator's capacity does not exceed either 1.5 times the customer's current average usage or 150 kilowatts (kW). The rider is available up to a total combined VRE cap, which was raised from 7 MW to 9 MW at the end of 2014 due to high demand (Fair Trading Commission Barbados, 2014). It was then raised again to 20 MW in February 2015 on the basis of the results of the Barbados Wind and Solar Integration study (GE Energy Consulting, 2015). All solar generators are currently smaller rooftop installations; there are no utility-scale renewable plants on the island, although large wind and solar developments of up to 10 MW are planned.

Barbados has made a voluntary commitment to cover 29% of its electrical load through renewables by 2029 (IISD Reporting Services, 2012).

The transmission system runs at voltages of 24.9 kV and 69 kV before being transformed down to 11 kV for distribution feeders.

GRID CODE LANDSCAPE

The island has two grid codes. One covers installations above 150 kW and the other installations at and below 150 kW aimed at units installed under the Renewable Energy Rider. No independent power producers (IPPs) have more than 150 kW capacity, which is the minimum level for larger installations in the grid code.

The Barbados Light and Power Company is responsible for writing and revising the grid codes. At the time the Barbados Wind and Solar Integration study (BLPC, 2015b) was published in February 2015, neither grid code contained requirements for FRT. One of the recommendations of the study was to include both frequency and LVRT requirements in the grid codes. In June 2015 the Renewable Energy Rider (RER) requirements for installations below 150 kW were revised to include these FRT requirements. By July 2015 the grid code for larger installations was also being revised in this light.

Under the Electric Light and Power Act 2013 (BLPC, 2013) the grid codes also have to be approved by the regulator, the Fair Trading Commission.

GRID CODE FOR INSTALLATIONS > 150 KW

The grid code for large installations was first published in April 2013, and a revised draft was published in May 2014 (BLPC, 2014a). It is intended for all distributed generators with capacity greater than 150 kW regardless of type or technology and connected to feeders at a voltage of 24.9 kV or below.

Some provisions, including protection parameters for voltage and frequency disturbances, are taken directly from IEEE standard 1547.

All generators must be "capable of operating in constant power factors anywhere between 0.95 leading and 0.95 lagging". This range can be adjusted by the Barbados Light and Power Company based on local conditions. The distributed generator is not allowed to actively regulate the voltage. The generator is expected not to contribute to short-term voltage fluctuations.

There is no explicit LVRT as of July 2015; the facility is expected to protect itself from voltage sags and swells caused by faults.

GRID CODE FOR INSTALLATIONS ≤ 150 KW

The 'Requirements for Grid Interconnection of Renewable Generation Systems' (BLPC, 2010) apply to small wind and solar systems not exceeding 150 kW in size. They were introduced as part of the original pilot Renewable Energy Rider in 2010. The interconnection requirements are less onerous than the grid code for larger systems. While the Renewable Energy Rider requirements include power quality and FRT requirements, there is no reactive power or power factor requirement. Compliance with the requirements should be demonstrated by submission of certification documentation from the inverter manufacturer in reference to the German VDE low voltage grid code (VDE, 2011) "or other equivalent standards".

GRID CODE LEGAL STATUS AND REVISION PROCESS

For small systems, fulfilment of the "Requirements for Grid Interconnection of Renewable Generation Systems" is a prerequisite for feeding in electricity to the public grid under the terms of the Renewable Energy Rider.

There are no explicit provisions in either grid code for the revision process of the technical requirements. However, the Barbados Light and Power Company consulted stakeholders when the grid code for systems of greater than 150 kW was revised in 2013. By July 2015 it was consulting stakeholders on including FRT requirements. Stakeholders include policy makers, regulators potential generation providers, electrical contractors, developers, engineers and installers (BLPC, 2014a).

GRID CODE OUTLOOK

The proposed national goal of covering 29% of annual energy load with renewables by 2029, which is under revision at the moment aiming at increasing it, will lead to situations where VRE feed-in is high compared to electrical demand. It could even possibly exceed the load at given times. In this situation it is very important that the majority of VRE units have frequency ride through capabilities. This was indeed a recommendation in the Barbados Wind and Solar Integration study (GE Energy Consulting, 2015).

In June 2015 the interconnection requirements for systems of less than 150 kW on the Renewable Energy Rider programme were modified to include voltage and frequency ride through capabilities. The Barbados Light and Power Company has been consulting with installers, manufacturers and VRE owners about the measures needed to implement FRT in existing systems. For PV systems where the inverter can simply be reprogrammed (even remotely) this may be required. For existing PV systems for which additional equipment has to be purchased, an exemption from the FRT requirements is under discussion. (BLPC, 2015b)

The interconnection requirements for the Renewable Energy Rider programme may also be incorporated into the grid code for systems larger than 150 kW. (BLPC, 2015b)

KEY CONSIDERATIONS

- Barbados is a small island power system with an as yet very low share of VRE generation but has plans to significantly increase this share. Today, the electricity production on Barbados relies on imported fuel;

- The existing grid connection codes on Barbados are currently being revised to obtain new requirements related to the higher VRE share planned. Distributed generators will need to be capable of defined voltage ride through and frequency ride through behaviour. Advanced features needed for very high VRE penetration levels are not yet under consideration. Instead, capacity limits are enforced for total installed VRE generation.

4.6 THE PHILIPPINES

POWER SYSTEM OVERVIEW

The Philippines consists of over 7,100 islands in the Pacific Ocean. There are three large synchronously independent networks. One is for the northern island of Luzon (peak load 8,305 MW in 2013), one for the central region of Visayas (1,572 MW) and one for the southern island Mindanao[6] (1,428 MW). Both the grid and generation capacity have struggled to keep pace with demand in recent years, especially on the island of Mindanao where capacity lags peak demand.

The Philippines obtains most of its renewable energy from its 3,521 MW of hydropower and 1,958 MW of geothermal power plants. In 2013 there was 17.4 MW of wind capacity and 0.3 MW of PV installations. Under the National Renewable Energy Program (NREP) the Department of Energy wants to increase the total installed renewable energy installed capacity to 15,304 MW by 2030 (Philippine Department of Energy, 2011). It has technology-specific targets including 2,378 MW for wind and 285 MW for solar.

GRID CODE LANDSCAPE

The Electric Power Industry Reform Act 2001 (Republic of the Philippines, 2001) mandated that the National Power Corporation privatise its generation and transmission assets, except for those necessary for missionary electrification. At the same time the newly created Energy Regulatory Commission drew up first versions of the grid code (Energy Regulatory Commission Philippines, 2001) (for the high voltage transmission system above 34.5 kV) and distribution code (Energy Regulatory Commission Philippines, 2001) (for distribution grid up to 34.5 kV). This was required in the Act.

The grid code is enforced and reviewed by the Grid Management Committee, which can make recommendations to the Energy Regulatory Commission about changes to the grid code. The Grid Management Committee was founded in 2005. It consists of stakeholders including the Energy Regulatory Commission, the National Grid Corporation of the Philippines, representatives of large customers, generators, the Department of Energy and the National Electrification Association.

The grid code provides the rules and requirements which govern the various users of the Philippines transmission system. The first version was published in 2001 and has been subsequently amended. Amendment No. 1 (Grid Management Committee, 2007) from 2007, like the original grid code, is focussed on synchronous generators and does not have any specific requirements for VRE generators.

Following the Renewable Energy Act 2008, which was introduced to support VRE generators, an addendum to the grid code was approved by the Energy Regulatory Commission in 2013 “establishing the connection and operational requirements for VRE generating facilities” (Energy Regulatory Commission Philippines, 2013). This addendum is incorporated in the draft Amendment No. 2 to the grid code (Energy Regulatory Commission Philippines, 2013), which was under revision in mid-2015 and was due to be approved by the Energy Regulatory Commission by the end of 2015.

In the addendum for VRE generators, specific requirements were introduced for large wind and PV parks connected to the transmission system depending on the size of installation. The grid code distinguishes between small generators and large generators. Large generators are those with aggregated capacity at the point of connection exceeding the following levels:

- 20 MW - Luzon grid

6 See comparison of peak load and generation capacity on www.ngcp.ph/

- 5 MW - Visayas grid
- 5 MW - Mindanao grid

Requirements for large generators include maintaining power quality, reactive power capabilities, voltage control, active power control, LVRT and Supervisory Control and Data Acquisition (SCADA) system.

Smaller PV units are exempt from the SCADA communication requirement and voltage and active power control, which allow the system operator to give set points to the large generators. In addition they do not have to support grid during LVRT by feeding in reactive power. For small wind generators there are also no requirements for reactive power capabilities.

The Philippines distribution code covers the lower voltage levels and takes over many of the provisions directly from the original grid code. The first version was written in 2001 and contains no specific requirements for VRE generators. By mid-2015 revisions to the distribution code were being considered to bring the requirements into line with the latest version of the grid code, including VRE requirements. The distribution grid code is enforced and monitored by the Distribution Management Committee.

GRID CODE LEGAL STATUS AND REVISION PROCESS

A Grid Management Committee consisting of power system stakeholders to monitor, review and enforce the grid code. The Grid Management Committee is responsible for drawing up amendments to the grid code, which must then be approved by the Energy Regulatory Commission. Similarly the Distribution Management Committee consists of distribution system stakeholders who monitor, review and enforce the distribution code.

GRID CODE OUTLOOK

By mid-2015, both the grid code and distribution code were being revised to include VRE requirements outlined in the addendum to Amendment No. 1 of the Grid Code (Energy Regulatory Commission Philippines, 2013). These revisions will bring the requirements for VRE generators into line with other international VRE grid codes.

KEY CONSIDERATIONS

- The Philippines have three major synchronous power systems and many smaller island systems. All systems are governed by the same grid codes, which contain requirements corresponding to the currently low VRE penetration rates.
- In accordance with the political VRE penetration targets, the grid codes are being revised to include more stringent generator requirements.

4.7 VRE GRID CODE EXPERIENCES FROM OTHER COUNTRIES

SPAIN: LVRT RETROFIT AND VOLTAGE CONTROL FOR WIND POWER PLANTS

The combined Spanish and Portuguese power system is, electrically, almost isolated. It has one AC connection to Morocco and only three AC transmission lines connecting Spain to France. In 2015 a 1,400 MW HVDC link between Spain and France was also commissioned. Given its electrical isolation, the Iberian peninsula might be considered to have a high VRE penetration. In 2014 the load in Spain varied between 18 GW and 39 GW while the wind and solar capacities installed were 23 GW and 7 GW respectively (ENTSO-E, 2014). Spain has introduced renewable energy control centres to monitor renewable generators in real time and, if necessary, regulate their power generation.

Given the high penetration of wind, the behaviour of wind power plants during system faults is critical. In the past, wind power plants in Spain were allowed to trip if the voltage dipped below 85% of its nominal value. However, the TSOs (Red Eléctrica de España –REE- in Spain and Redes Energéticas Nacionais –REN- in Portugal) realised that this could lead to widespread outages during fault incidents. REE therefore introduced an LVRT specification in 2006, at which point there was nearly 12 GW of wind in Spain. In 2007 a royal decree enforced the LVRT specification. It made it mandatory for all new wind plants and introduced a higher feed-in tariff for existing wind generators and more recently PV generators to retrofit. This was to enable them to fulfil the new regulations. Wind plants that did not comply with the LVRT would be considered first for curtailment if stability problems arose. Furthermore, generators could lose renewable energy subsidies altogether if they fail to justify technically to the government why they could not be retrofitted (Pöller, 2011). By 2009, more than 10 GW of wind plants had been retrofitted.

In 2007 Spain also introduced incentives to encourage wind plants to contribute towards regulating the voltage (Cena Lazaro and Gimeno Sarciada, 2008). They were either given a bonus or penalised depending on their power factor at different times of day. At peak hours wind plants were incentivised to raise the voltage and during hours of low demand they were incentivised to lower it. However, this scheme introduced at least two problems. First, the simultaneous connection and disconnection of reactive power compensation devices like capacitor banks at the beginning and end of the peak periods caused sudden spikes in voltage levels. Secondly, the different hourly settings did not distinguish between workdays and holidays, which created a destabilising effect. In 2009 legislation was introduced for more reasonable power factor requirements. The renewable energy control centres issued set points and dynamic voltage support (López, 2010).

DENMARK: DELTA ACTIVE POWER CONSTRAINT FOR WIND POWER PLANTS

Denmark has been a pioneer in the integration of both onshore and offshore wind. In 2014 wind energy generated was equal to 40% of Denmark's annual electrical demand. At the end of 2014 Denmark had 4.9 GW of wind (3.6 GW onshore and 1.3 GW offshore) and 0.6 GW of PV while the load varied in 2014 between 2.3 GW and 6 GW. This meant there were many hours in the year when wind generation exceeded electrical demand. Denmark has strong grid interconnections with Germany, Norway and Sweden, so that exporting its excessive generation is an option.

The Danish TSO Energinet.dk has also been a pioneer in the development of operational practices to integrate VRE generation and the corresponding grid codes requirements. One such example is the introduction of delta active power constraints. Delta active power constraints require the power plant to reduce its active power output below the power available. This means it can provide an upward regulating reserve and thus help to regulate the frequency when this drops below nominal (see section 3.3). Delta control functionality is required in the Danish wind grid code (Energinet.dk, 2015) for all wind power plants with a total power output of more than 25 MW at the point of connection. The delta control must be controllable with external signals and "must be commenced within two seconds and completed no later than 10 seconds after receipt of an order to change the set point". Delta control is usually only provided when the wind feed-in is already high.

4.8 NATIONAL TECHNICAL REQUIREMENTS COMPARED

The different power system properties of the countries were summarised in Table 5 at the start of this chapter. Table 6 summarises the main grid code requirements for each country.

Table 6: Comparison of case study technical requirements.

Requirement	Germany	Ireland	Australia	Barbados	Philippines
Power quality	Flicker, harmonics, voltage fluctuations	Flicker, harmonics, voltage fluctuations	Flicker, harmonics, voltage fluctuations	Flicker, harmonics, voltage fluctuations	Flicker, harmonics, voltage fluctuations
Reactive power capability	Power factor from 0.9 leading to 0.9 lagging	More than 12% of Pmax, must be able to provide Q* of +-33% of Pmax (corresponds to pf of 0.95 at Pmax)	Must be able to provide Q at 39.5% of its active power rating at all levels of voltage and active power output	Power factor from 0.95 leading to 0.95 lagging	For large wind plants with more than 58% of Pmax, must be able to provide Q at +-20% of Pmax
Frequency support	Frequency-power output curves	Frequency-power output curves; wind turbines must be able to restrict ramping	Frequency-power output curves	None available	Must be able to limit active power during over-frequency; large plants must be able to limit ramping
LVRT	Stay connected at 0% V for 0.150 seconds; must provide active and reactive power	Stay connected at 15% V for 0.625 seconds; must provide active and reactive power	Stay connected for at least 0.430 seconds; must provide reactive power during fault and active power 0.1 seconds after fault	None available	Wind must stay connected at 20% V for 0.625 seconds; must provide active and reactive power after 0.15 seconds; PV must stay connected for 0.15 seconds at 0 V, then until 0.625 seconds at 30%
Remote communication	Two-way, instructions to VRE may include active power set points, voltage control set points and start/ stop instructions	Two-way, wind turbines must take set points on active power, frequency control and voltage control	Two-way; large VRE plants must take set points to reduce active power; must report large variety of status information	Two-way; plants must report variety of status information; control signals include breakers, active power and voltage control	Two-way, instructions to VRE may include active power set points, voltage control set points and start/stop instructions

Overall, there is a correlation between power system characteristics, such as VRE share, and the stringency of grid code requirements. For example, Barbados has a low share of VRE contributing just over 1% of its electricity demand, and its grid code requirements are relatively easy to fulfil with no FRT or frequency control requirements. However, the grid code was being revised as of April 2015 to add frequency and voltage ride through. On the other hand, Ireland has a relatively high share of VRE covering just over 15% of its electricity with wind. At the same time it is part of an island system with Northern Ireland so that the entire island of Ireland must regulate its own frequency. This contrasts with Germany, for instance, which has strong AC interconnections. For this reason, the Irish grid codes pay particular attention to frequency control requirements and restricted ramping rates as well as the ability to curtail wind power plants. This is due to worries about frequency stability with high levels of non-synchronous generation.

More reactive power capability is required of VRE generators connected to the distribution grid in Germany than in Barbados (down to power factor 0.9 for generators larger than 100 kW in the low voltage grid compared to 0.95 in Barbados). This again reflects the different level of VRE share. Where there is more VRE, more reactive power capability is required given that there is a higher likelihood that VRE generators cause over-voltage problems in the network. Reactive power is often the only means of active voltage control on the feeders, especially in the distribution grid. These considerations demonstrate that country-specific requirements are reflected in the grid codes.

However, there are many similarities between the grid codes. They differ generally only in how grid code requirement parameters are set, rather than in the types of requirements made. This has historic origins. Countries at the forefront of VRE integration have often been the first to test and develop new requirements. Other countries have then used these as a reference for their own grid codes. Thus network operators have been able to share experience in setting VRE generator requirements and avoid the mistakes made by early adopters of VRE technology. One example is the 50.2 Hz problem in Germany.

In addition, a degree of commonality between grid codes is in every country's interest, because it makes manufacturer compliance easier and therefore reduces costs.

4.9 COUNTRY CASE STUDY FINDINGS

Some concluding findings can already be drawn from the review of the diverse grid codes in the case studies, and are outlined below.

- In the past, network operators have incorporated grid code experience from countries at the forefront of VRE integration, thus avoiding the mistakes of early adopters;
- Given that manufacturers have now developed VRE generators which can meet many grid code requirements, there is little additional cost in meeting basic grid code requirements (see section 3.5 on ease of Implementation);
- Grid codes often need country-specific requirements to cater to local power system characteristics. Assessing these country-specific needs and their cost-benefit trade-off requires expertise and knowledge of the country's power system. For example, island systems which must regulate their own frequency may need stricter frequency control requirements while countries with weak areas in their grid may require more reactive power capability. For interconnected systems, the condition of integration with other countries has to be considered in addition to the technical properties. This is because agreements for the exchange of energy and services can make a direct impact on grid code requirements;

- Grid codes are often separately adapted to specific voltage levels or transmission and distribution levels or different classes of generator by maximum power output;
- Requirements that are too strict may put off some manufacturers from supplying their products to the market;
- When the network operator is drafting or revising the grid code, other stakeholders should also be consulted. This includes, for example, generator owners and operators, regulators, developers, installers and manufacturers (see Section 2.4 'Grid code development process');
- Countries without the resources to certify generator compliance with grid code requirements can require certification to the requirements of similar countries or regional bodies instead (see section 6.4 'Generator compliance');
- A regular grid code revision process can help incorporate changes or new requirements as the need arises or circumstances change; this is best done in a process transparent to all stakeholders.

Further discussion of recommendations and best practice is provided in chapter 7.

Grid codes often need country-specific requirements to cater to local power system characteristics. Assessing these country-specific needs and their cost-benefit trade-off requires expertise and knowledge of the country's power system

Chapter 5

Relationship Between Regional and National Grid Codes

5.1 REGIONAL AND NATIONAL GRID CODES

Regional grid codes apply to a regional group of countries. Typically regional grid codes do not replace national grid codes, but provide a common framework for grid code requirements instead and set minimal standards that all national grid codes must meet. This allows the flexibility for national grid codes to set country-specific requirements. System operators are also heavily involved in drafting and revising regional grid codes to avoid conflict. The TSOs of the individual countries involved are exclusively responsible for developing the Nordic Grid Code, for example. The network codes published by ENTSO-E are drafted by a board of experts sent by the system operators, who then regularly consult with the other stakeholders. National and regional grid codes must also often be approved by national regulators.

By early 2015 there were very few regional grid codes in existence. Where they have been or are being implemented, the main driver has been the harmonisation of rules on power trading between countries rather than VRE-specific requirements. However, regional VRE grid codes are expected to gain in importance for two reasons in particular. Firstly, some grid code requirements depend on the overall VRE share of the interconnected system across several countries. Secondly, cross-border electricity trading facilitates VRE fluctuation balancing.

5.2 BENEFITS, OPPORTUNITIES AND CHALLENGES

The advantages of regional VRE grid codes include:

- Clarity and simplicity for all stakeholders acting internationally within the region, such as manufacturers who sell their generators in different countries or VRE operators who sell power across borders;
- Cost savings for network operators in areas like certification so long as countries can pool their resources;
- Cost savings from harmonised grid code requirements, which makes it easier for manufacturers to meet diverse national requirements;
- Where countries in a particular region share common grid code requirements, the investment in writing and maintaining the separate national grid codes can be reduced.

Regional grid codes provide a coherent framework within which the power system can be operated more efficiently. They may allow more efficient system operation and a higher share of renewable energy and thus lower cost in the long run. The use of a regional grid code for generator requirements ensures either internationally harmonised requirements or at least an internationally harmonised grid code structure. Both of these make it easier for stakeholders to manufacture and operate assets in different countries, and for system operators to use their interconnectors more efficiently to trade more renewable energy. However, great care has to be taken when developing regional grid codes. Local and national structural peculiarities have to be taken into account, especially if the grid code covers a large area with several synchronous zones - such as the ENTSO-E Network Codes. For countries with existing grid codes, drafting a good regional grid code and harmonizing all national and local documentation may mean a great deal of effort and demand major upfront investment. Conversely regions lacking a grid code may save costs by pooling resources to write a common regional grid code.

5.3 EXISTING REGIONAL GRID CODES AND RELATIONSHIP WITH NATIONAL GRID CODES

At the moment regional grid codes are predominantly used in areas with a high amount of cross-border energy transfers. They facilitate international energy trading and govern the technical consequences of such transactions. Such grid codes are thus mainly focused on trading rules, interconnectors and congestion management. Cross-border energy trading in Europe has been increasing with the rising share of VRE, and transactions directly influence generator dispatch and grid stability. Regional grid codes may also contain specific rules for VRE generators, which need to be harmonised with or replace the national requirements.

Two regional grid codes exist in Europe, the Nordic Grid Code (Nordel, 2007) and the ENTSO-E Network Codes[7] (ENTSO-E, 2013). The Nordic Grid Code has been used by Denmark, Finland, Norway and Sweden and regularly revised since 1999. However, the ENTSO-E Network Codes have been developed over the last few years and are now being signed into EU law. This will mean harmonizing all European grid codes including the Nordic Grid Code to comply with the structure and requirements of the ENTSO-E Network Codes.

Both grid codes are structured in a similar way, and the ENTSO-E network codes are more extensive than the Nordic Grid Code. Large parts of both grid codes are made up of market rules and operational procedures that are not directly relevant to VRE integration. A section on generator requirements exists in both: the Network Code on Requirements for Generators (NC RfG) in the ENTSO-E Network Codes and the connection code in the Nordic Grid Code. In both cases, VRE generators generally have to fulfil the same requirements as conventional generators. However, they are sometimes exempt from certain requirements like the provision of inertia or reserve power.

NORDIC GRID CODE – CONNECTION CODE

Section 4 of the connection code in the Nordic Grid Code 2007 currently applies and is a collection of rules agreed by the TSOs of the four Nordic countries. Requirements distinguish between generator technologies in different countries. They take into account the fact that Denmark, which produces almost all its electricity from coal and wind power, may not have the same needs as the Swedish system, which relies heavily on nuclear and hydropower. Detailed requirements are given for conventional generators while the VRE requirements are less exhaustive. The national TSOs and local DSOs are specifically given the authority to draft their own grid codes. These may impose additional rules on generators but must at least include all the requirements given in the Nordic Grid Code. The national grid codes have primacy over the requirements specified in the Nordic Grid Code.

7 http://networkcodes.entsoe.eu/

ENTSO-E NETWORK CODE GENERATOR REQUIREMENTS

The ENTSO-E Network Codes are described on the ENTSO-E web site as "a flexible framework which allows some parameters to be set on a national basis (within ranges specified in the network codes), and others at pan-European level". These codes are the result of a mandate by the European Commission. Unlike the Nordic Grid Code, which is an agreement between the TSOs involved, the ENTSO-E Network Codes will become EU law which supersedes national legislation. A section on generator requirements entitled the ENTSO-E Network Code Requirements for Generators (NC RfG) was completed in 2013 and in early 2015 was still awaiting approval by European stakeholders. All European grid codes, including the Nordic Grid Code, have to be harmonised with the ENTSO-E Network Codes - a large project in each country over the coming years.

It is structured similarly to the Connection Code of the Nordic Grid Code, but is applicable in a much greater area. This covers all five ENTSO-E member country synchronous zones (continental Europe, Great Britain, Ireland, Nordic region, Baltic). Requirements are therefore even less specific and more often distinguish between countries, technologies and synchronous zones. Requirements like LVRT time frames or power factors are either given as relatively undemanding minimum requirements or ranges within which the system operators can set their rules. The NC RfG for the most part therefore has the character of an eventually legally binding guideline covering topics and requirements to include in a grid code and how to structure it. It is officially developed with the goal of integrating more renewable energy and enabling cross-border energy trade in the EU. It covers all generator types distinguished by size and voltage level as well as direct or converter-based grid connection. Requirements only apply to new generators. The entire range of ENTSO-E Network Codes is being revised and amended. However, according to ENTSO-E, "the need for a pragmatic approach is understood by all parties. If there is a need for an urgent amendment of a code, the process should not be onerous" (ENTSO-E, n.d.).

Some requirement ranges specified in the NC RfG are given in Table 7. They are compared to the German grid code requirements, which have yet to be harmonised with the NC RfG.

Table 7: Comparison of selected ENTSO-E requirement ranges and corresponding German transmission code requirements.

Requirement	ENTSO-E NC RfG,, connected at minimum110 kV	Germany TC 2007 at minimum 110 kV
Required power factor range	0.75 in both directions for VRE power plants > 75 MW, 0.95 in both directions for smaller units	Three different ranges - one can be selected : a) 0.975 cap.a – 0.9 ind.b b) 0.95 cap – 0.925 ind. c) 0.925 cap. – 0.95 ind. Offshore: 0.95 cap, - 0.925 ind.
LVRT	140 – 250 msc, voltage threshold between 0.05 and 0.3 p.u.d	150 ms at 0.0 p.u. or 150 ms at 0.45 p.u. and 700 ms at 0.70 p.u.
Frequency range without disconnecting	Different requirements for each synchronous zone. Continental Europe: 47.5 – 49.0 Hze: to be defined by TSO, no less than 30 minutes 49.0-51.0 Hz: unlimited 51.0-51.5 Hz: 30 minutes	47.5 – 48.0 Hz: 10 minutes 48.0-48.5 Hz: 20 minutes 48.5-49.0 Hz: 10 minutes 49.0-50.5 Hz: unlimited 50.5-51.5 Hz: 30 minutes
Voltage range without disconnecting	Different requirements for each synchronous zone and voltage level. Continental Europe, 110 – 300 kV: 0.85 – 0.90 p.u.: 60 minutes 0.90 – 1.118 p.u.: unlimited 1.118 – 1.15 p.u.: To be defined by the TSO, no less than 20 minutes	Same requirements for 110, 220 and 380 kV: 0.87 – 0.90 p.u: 120 minutes 0.90 – 1.10 p.u.: unlimited 1.10 – 1.16 p.u.: 30 minutes

[a] capacitive [b] inductive [c] millisecond [d] per unit [e] hertz

5.4 PLANS FOR FURTHER REGIONAL CODES

Regional grid codes are mainly used in areas where cross-border trading is important in order to set coherent rules for power system operation in all participating countries. By early 2015, regional grid codes were being drafted for the Eastern African Power Pool region (SNC Lavalin, 2010) and the Greater Mekong Area (Jude, 2013) in South East Asia. Both are based on the Nordic Grid Code because the prime purpose of the regional grid code is to facilitate energy trade. In these areas power trading is used to balance out seasonal fluctuations in hydropower, which was also the origin of the Nordic Grid Code. The Central American Electrical Interconnection System (Sistema de Interconexión Eléctrica de los Países de América Central –SIEPAC-) is also considering drafting a regional grid code to govern cross-border trade.

Regional grid codes provide a coherent framework within which the power system can be operated more efficiently. They may allow more efficient system operation and a higher share of renewable energy and thus lower cost in the long run.

Chapter 6

Additional Grid Code Design and Implementation Considerations

As already described in section 2, the design of an adequate grid code for a given system touches issues beyond the immediate definition of technical requirements. This section discusses several of these concerns. All need to be considered in the design and revision processes of grid codes in changing systems.

In general, it is not enough to place technical capability and behaviour requirements on assets to ensure an electrical power system stable and runs securely. Grid operators make active use of ancillary services provided by the assets connected to manage the operational requirements of the system. Provision of ancillary services relies on the availability of corresponding technical capabilities on the asset level. The technical requirements in grid codes enforce this availability of capabilities. This is discussed in section 6.1.

Generation assets of various technology types and also of a very wide range of installation sizes are connected to electrical power systems and are required to fulfil the technical criteria. Depending on the technology, meeting the requirements may or may not have a major impact on asset cost. In practical terms this implies that grid codes should specify different requirements for different generator types and sizes. Section 6.2 provides more information on this differentiation.

Experience in pioneer countries has shown that existing grid code requirements can harm system security when a previously unforeseen VRE share is reached within only a few years. In such cases, retrofitting old (existing) generation may turn out to be the only way to maintain system security. Retrofitting is discussed in section 6.3.

Last but not least, technical requirements are only meaningful if they can be relied upon. In other words, there must be a way to verify that assets actually comply with the rules set down in the grid codes. Hence, grid codes also need to deal with the question of how to guarantee compliance of generators. Section 6.4 deals with this topic.

6.1 ANCILLARY SERVICES

Ancillary services are the system facilities that the system operators use and manage for operation. These services are provided by network equipment, generators and increasingly also storage and active consumers through their availability for dispatch and reactive power contribution. Usually, ancillary services include the following:

- System balance and frequency control
- Reactive power and voltage control
- Congestion management

Grid codes can require generators to have the technical capability to provide selected ancillary services but the actual use of these services may be governed either by the grid code or by other regulations.

SYSTEM BALANCE AND FREQUENCY CONTROL

Most grid codes require conventional generators above a certain size to be equipped with appropriate automatic turbine speed governors to be able to provide primary operating reserve (see glossary). Although the primary reserve capability is then a prerequisite for grid connection, it may not actually be used in all power plants. In most countries, primary reserve, like all reserve power, is procured by the TSOs through the reserve power market. Usually, generator operators are paid for making their generator capacity available for a certain time, not just for the energy actually used. Depending on the country, used energy may be paid for too. Secondary and tertiary reserve is also procured by reserve power markets. Generators have to undergo a prequalification process to be allowed to take part in the reserve power market, in which their technical capability to fulfil the necessary requirements has to be proven. This prequalification process currently often excludes VRE generators or generators connected to the medium and low voltage grid. Adjustments to the regulatory frameworks that go beyond the grid codes themselves will have to be made to be able to procure reserve power from capable VRE generators.

The availability of secondary reserve is essential to grid stability and security of supply so it may also be subject to grid code regulations. For example, German TSOs are allowed to order generator operators to provide secondary reserve power in case not enough reserve power that can be procured.

REACTIVE POWER AND VOLTAGE CONTROL

Large industrial consumers may be required to pay for reactive power if they cannot supply it themselves. This money usually goes to the grid operator with the purpose of installing reactive power compensators. Reactive power from generators including those based on VRE is used for local voltage control. It is a prerequisite for grid connection but has not often been financially rewarded. The rising demand for local reactive power has led to the introduction of reactive power markets in Great Britain, Australia, India, Belgium, the Netherlands and Canada. In Great Britain, reactive power capabilities remain a prerequisite for grid connection except in the low voltage grid but the amount of 'produced' reactive power[8] is financially rewarded. Financial rewards are also given for capabilities that exceed the grid code requirements. This is applicable for both conventional and VRE generators. Reactive power is purchased by the grid operator, and the cost is passed on to the consumers via grid charges. (Papalexopoulos and Angelidis, 2006) (National Grid Electricity Transmission plc, 2014) Reactive power markets provoke considerable controversy. This is because there is no clear answer to the question of ownership. Should voltage quality (and thus reactive power) be a public good to be paid for by grid charges or a private good paid for directly by the consumer? The latter includes the grid operator, who acts as a customer when the grid itself needs reactive power due to high loading. In addition, if reactive power capability is a prerequisite for grid connection, all generator operators have to invest in those capabilities. However, those in areas with high local reactive power demand can use this capability to actually make money. (Brückl, 2013)

CONGESTION MANAGEMENT

In a free energy market, generator dispatch is determined by merit order. This means the unit with the lowest marginal cost will go online first, and more expensive units come online as demand rises. VRE usually comes early on due to its low marginal cost. It also often enjoys priority feed-in privileges and is thus dispatched first independent of any market-based dispatch based on marginal cost. The residual

8 Technically, reactive power is not 'produced' as it is energy used to build up electromagnetic fields, and is returned once the field decays. Reactive power markets use the pseudo-unit of volt-ampere reactive hour, which is a function of time, apparent power and generator power factor.

or net load that remains has to be covered by conventional power plants. Where grid congestion could occur, the grid operator is required to manage congestion via various means such as redispatching conventional generation resources or VRE active power management.

VRE generation cannot usually be redispatched but only curtailed in one place and replaced by conventional generation elsewhere. In many legal frameworks, such VRE 'curtailment' is only allowed if grid congestion cannot be resolved using conventional power plants. This is the case if the grid is congested in areas with very high VRE feed-in or if conventional power plants cannot be ramped down further due to must-run conditions.[9] Redispatch and curtailment are either dealt with in the grid code or in other regulations, which depends on the country and region.

6.2 REQUIREMENTS FOR DIFFERENT GENERATOR TYPES AND SIZES

Differences between generator types have to be taken into account when designing grid codes. It may not be technically or economically feasible to require the same capabilities from all generators. Indeed, inverter-based VRE generators may find it impossible to fulfil some requirements based on the properties of synchronous generators. The demand for contribution of inertia or high short circuit current may especially prevent the installation of PV units and inverter-based wind generators. This is because synthetic inertia technology is currently still under development (see section 3.4).

Requirements for large VRE installations such as wind parks are often stricter than for single units. At first glance, large installations do have a higher impact on the system than smaller units. However, requirements that are too stringent may simply motivate generator operators to circumvent them by installing several small units instead of a single large one. If the limit for stricter technical requirements for wind parks is set at 10 MW, for example, investors are very likely to prefer to build two 8 MW wind parks than one 16 MW park. Different requirements for differently sized VRE generators have to be carefully considered because the actual share of VRE is more important to system stability than the size of the single unit or installation. Using size to differentiate between units is one possible way. Another is the voltage level of the connection and a third is technology type. They can be combined, providing multiple ways of differentiation in a given grid code ruleset. They may or may not coincide in the actual units fitting into the different categories.

The important point is to weigh up the costs of stricter requirements appropriately while keeping the system stable and also reaching the VRE targets. It may be sensible to have more relaxed requirements for small units or units in the low voltage grid to avoid excessive cost. This may, however, lead to a rapidly rising share of such units up to a point where stricter requirements are necessary. Striking the balance between cost, VRE targets and system stability may not be easy and will be a compromise either way.

6.3 RETROFITTING OLD GENERATORS

Grid codes usually distinguish between requirements for newly built VRE generators and those for existing VRE generators. If the need for new requirements is recognised early enough, old generators can be sufficiently few in number to avoid retrofit to comply with the new regulations. If the installed capacity of old generators is so high that grid security is already compromised, which happens when grid code revisions are made too late, they may need to be retrofitted to match new regulations. This retrofitting will usually be limited in scope, adding only the functionalities needed to solve the existing problem instead of upgrading the units to fulfil all new grid code requirements.

It is not common practice to simply require generator owners to make costly upgrades to their assets. This is because compliance with the grid code at the time of initial connection usually grants them the right to feed power into the grid without a time limit. However, the feed-in tariff and priority feed-in may eventually expire (e.g. to 20 years). Financial incentives can be created to encourage retrofit.

9 There are several reasons for must-run conditions in conventional generators. These include, for instance, the inflexibility of old nuclear power plants, cogeneration plants that need to cover a heat demand or plants that have to be kept online for ancillary services.

Alternatively, the grid operator or government (and ultimately the electricity users) may contribute to covering costs in addition to or instead of the generator owner.

Retrofit measures

Examples of retrofitting measures necessary due to a faster than predicted growth in VRE generation are older German PV units retrofitted to avoid the 50.2 Hz problem described in section 1.3. Likewise, more than 10 GW of installed wind power was retrofitted in Spain to provide LVRT capabilities from 2007. Around EUR 190 million was paid for the German PV retrofit (Bundesministerium der Justiz und für Verbraucherschutz, 2012) by the electricity user half through grid charges and half through the renewable energy charge without affecting the generator owners in any way. Spain dealt with the problem differently through a royal decree. This introduced a higher feed-in tariff for existing wind generators (and more recently PV generators) that could certify that the new regulations had been fulfilled. At the same time, all others were to be considered first choice for curtailment if stability problems arose. Furthermore, generators could lose renewable energy funding altogether if the owner did not provide a technical justification as to why they could not be retrofitted. (Ruiz Gillen, et al., 2009)

Retrofitting old generators can vary in difficulty, depending on the requirements that have to be met and the advance in technology since the unit's installation. The German 50.2 Hz problem was relatively easy to resolve with a software update. It set the frequency at which the unit would disconnect from the grid at a slightly different value for each generator. Retrofitting Spanish wind turbines to provide LVRT capability required more extensive hardware updates in most installed wind turbines. Old fixed-speed wind turbines simply could not ride through grid faults and had to be upgraded with additional Flexible Alternating Current Transmission System (FACTS) installations that provide the desired capacities. More modern variable speed wind turbines could often be retrofitted at machine level, and units had to be modified and tested in the field. The extensive retrofit operation suffered from a lack of supplies and human resources. Most manufacturers and experts were concerned with the installation of new turbines and therefore often not available for retrofitting tasks, which severely delayed the process. (Ruiz Gillen et al., 2009)

6.4 GENERATOR COMPLIANCE

Setting technical requirements for generators to be connected to the grid has little value if compliance with the rules cannot be verified. For this reason, compliance verification mechanisms have to be included in grid codes. There are different strategies with differing costs and degrees of feasibility depending on the country and region the grid code applies to. Processes should thus be clearly defined and adapted to the specific country, grid and grid code.

The most resource-intensive method for verifying compliance is to perform on-site tests on each new VRE installation with the cost depending on the requirement to be tested. For example, power quality and reactive power capabilities can be assessed easily using power analysers at the point of common coupling. However, some grid requirements are harder to test: verifying on-site LVRT performance requires specialised equipment, which is expensive and costly to transport. Such equipment may be beyond the means of smaller network operators.

The more common method is to require a grid code compliance certificate for each unit installed. Certificates can be issued by several different accredited parties. Usually, one unit of each type is tested for compliance with one or more grid codes at a test site, and a compliance certificate is granted to all units of the type. Countries may be able to pool their resources for certification and avoid expensive duplication of test facilities. To achieve this, their grid code requirements need to match. Alternatively they need to be willing to accept a certificate for compliance containing requirements from another country's grid code that are stricter than their own (see section 5: 'Relationship between regional and national grid codes).

If requirements apply at the point of common coupling of multiple generators, such as in a wind power plant, the use of type certificates only may be insufficient. Generators may behave differently if grouped with other generators of the same or a different type, especially in large installations that have their own collector grid. In these cases, the whole installation may have to be tested again on site for grid code compliance, which is more expensive than simple type certification. However, if several installations of the same configuration exist, only one may have to be tested to obtain a project certificate.

Grid operators may demand a simulation model of each generator as a prerequisite for connection. This must in some jurisdictions be validated and certified by an independent accredited party[10]. These models are used to determine the static and transient behaviour of the grid. However, they can also be used for grid code compliance assessment if the corresponding functionalities are modelled, validated and certified. Certified simulation models of single units can also be used to assess the behaviour of a larger installation with known topology, avoiding costly on-site testing. Furthermore, as the grid code gets updated over time, it is essential for the system operator to know which generators comply with what version of the code to predict the system's behaviour. Older units may be compliant with newer versions too if their capabilities exceeded the grid code requirements at the time of their installation. Type certificates and simulation models help to keep track of generator compliance.

Setting technical requirements for generators to be connected to the grid has little value if compliance with the rules cannot be verified. For this reason, compliance verification mechanisms have to be included in grid codes.

10 Example: the German medium voltage grid code requires generator models to be certified by an independent accredited certifier. (BDEW, 2008)

Chapter 7

Recommendations

This chapter makes recommendations on how to develop and revise grid codes for the integration of a higher share of VRE. Specific recommendations are based on lessons learnt especially by countries that have pioneered VRE integration. The availability of facilities necessary to check for generator compliance will need to be respected.

7.1 ENSURE AN APPROPRIATE PROCESS FOR DEVELOPING A NATIONAL GRID CODE

The technical issues discussed in this report are relevant to all power systems with VRE generation regardless of market structure. Grid codes are necessary in unbundled power systems with separate ownership of generation and grid infrastructure. However, a grid code is required even in a vertically integrated system.

Grid codes may apply to a region, country or area within a country. Depending on country and power system size, a synchronous system may comprise several countries (e.g. European synchronous systems, Central America). Alternatively, one country may have several synchronously independent power systems (e.g. Japan, the US). Before developing a grid code, the area of applicability has to be established.

Based on the area of applicability, the stakeholders involved in the drafting process have to be identified. These usually include policy makers, regulators, grid operators and/or utility companies, generator owners, installers and manufacturers as well as consumers. The grid code development process, including revisions, have to be transparent: the role of all stakeholders involved as well as their active engagement, needs to be clear[11].

Grid code development has to take local conditions into account when power systems have sufficiently different characteristics from the neighbours, and harmonisation is not technically or politically feasible. Studying other countries' grid codes and adopting their requirements or structural elements is acceptable and encouraged, provided requirements are checked for compatibility with local conditions. Simply copying another grid code in its entirety is not a good practice and should be discouraged. Local conditions should be assessed through a grid study before writing the grid code. Grid codes should be the result of detailed studies of the system characteristics and behaviour, requiring the technical knowledge and experience of the network operators.

Countries and regions in which VRE generation is just developing can profit from lessons learnt by pioneering countries. This allows them either to avoid problems early on or at least keep a watchful eye on issues that might become critical in their own system. Requirements that would have been

11 The European Commission has published Stakeholder Consultation Guidelines (European Commission, 2014)

too demanding when the pioneering countries embarked on VRE integration may now no longer be a problem due to widespread technology availability.

A coherent and well defined grid code structure is desirable, such as those used in the ENTSO-E Network Codes. Equally desirable is a clear boundary between energy legislation and technical regulations. Some of the pioneering countries have a grid code structure that has grown over time. This has resulted in a multitude of different documents and requirements with a high level of complexity and undesirable overlap between grid code and renewable energy legislation. This can be avoided by introducing a well-defined structure from the beginning.

The expected and desired future development of the power system has to be taken into account when developing a grid code. A grid code designed for the status quo may become obsolete very quickly of the VRE share rises or other changes occur in the structure of the power system. This can endanger operational security and grid stability. However, this does not eliminate the need for regular grid code revisions.

Grid codes have to be revised and updated regularly to keep up with technological and economic development. Setting up defined, periodic procedures to check the grid code and revise it as new issues arise is highly recommended. Besides keeping the requirements up to date, this also helps to retain a clear and concise grid code structure. A balance has to be struck to decide how often to revise the grid code. Revisions that are too frequent may be too costly. However, a grid code updated only after an issue has already become evident may be too late, and costly retrofits may become necessary.

7.2 CONSIDER THE SPECIFIC CONDITIONS FOR DEVELOPING TECHNICAL REQUIREMENTS

Technical requirements specified in a VRE grid code have to take specific conditions into account. This is because requirements that are perfectly sensible for one system may be too demanding, not demanding enough or completely irrelevant for a system with different characteristics. Key factors that determine the character of the power system and thus the need for technical requirements are outlined below:

- Size of the power system in terms of geography and electricity (line lengths, peak power, minimum power);
- Interconnection level (strongly interconnected, weakly interconnected, synchronously independent with or without non-synchronous connections to other power systems, agreements with other countries on services interchange);
- Voltage level and role of the grid - requirements in an extra-high voltage transmission grid may differ strongly from those in a low voltage distribution system;
- Distribution of load and generation in terms of geography as well as vertically across the voltage levels;
- Characteristics of conventional generation, unit commitment and dispatch regime (e.g. a country like Sweden with a high share of nuclear and hydropower may encounter different VRE integration problems than Ireland with a system based on natural gas);
- Renewable energy policy, which is directly linked to VRE development and may grant VRE generators special privileges;
- Present and expected VRE share;
- Market size - countries with a large market may induce new technological developments by setting demanding requirements, while small countries with less market power may have to work with what is currently available;

- Operational practices - how the system is operated at the moment and the operation plan for the future (e.g. reserve allocation, dispatch scheduling time frames, security criteria). This may influence how demanding and detailed the connection requirements are.

These dependencies mean there is no easy way of avoiding the cost of drafting a grid code tailored to the specific system. Using a carbon copy of another country's grid code may only be feasible in particular cases with very similar grid topology and generation structure. Even in these cases, each requirement must be checked for relevance and applicability before adapting the code. However, the use of information from other countries' grid codes, as well as from international technical standards, is highly recommended because it avoids duplicating research results already available.

Different requirements for different voltage levels, generator types and sizes have to be considered in terms of the characteristics of the entire system. Strict requirements for small generators may hinder development because of the higher cost. A large number of small generators in the distribution grid may on the other hand have a quite large impact on system stability and the transmission grid, which may make stricter requirements necessary. A balance has to be struck between the additional cost of requirement implementation and system stability.

7.3 SUPPORT NATIONAL POLICIES AND LEGISLATION WITH REGULATORY MEASURES

Policy support for renewable energy and grid code requirements on VRE both have a direct impact on VRE development within a country and have to be co-ordinated to avoid conflicts. The boundaries between energy legislation and the grid code, and thus between the responsibilities of grid operator or utility and government, have to be clearly defined. In some cases, technical requirements were directly set by laws or directives in the early days of VRE integration. For clarity, it is recommended that technical requirements are set only in the grid code while support schemes for compliance with grid codes should be directly mandated by legislation.

Grid operators or utilities need a legal basis to enforce the grid code. This can be a law or directive directly mandating grid code compliance for all generators. More often, the grid operator is required by the regulator to ensure security of supply and thus to take all measures necessary to do so. This includes grid code development and enforcement.

Furthermore, the grid code requirements should support renewable energy policy. If there is a strong support scheme for one or several particular technologies, the grid operator should avoid making them subject to extremely restrictive technical requirements. However, it must choose requirements in such a way that even very quick development does not endanger grid security. In regions with a large potential market, such requirements may induce new technological developments.

7.4 ENSURE GENERATOR COMPLIANCE

Compliance verification mechanisms are crucial for the successful use of a grid code. Setting requirements for generators without being able to check whether they actually fulfil them has little value. Depending on local conditions and infrastructure, there are several different compliance verification methods. The resources available for compliance control also determine which technical requirements are enforceable and may thus limit the scope of the grid code. Countries or grid operators without the resources to certify generator compliance with grid code requirements themselves can instead require certification in terms of the requirements of similar countries or regional bodies. Pooling resources through a regional grid code or at least a regional certification scheme is recommended for small countries and grid operators. This includes, for example, the hundreds of distribution grid operators in Germany that already use the same grid code and certification scheme.

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Annexes

Annex A: Technical requirements for VRE grid codes

Only a high-level description is provided in chapter 3 without details of technical requirements. This annex provides more lower-level detail of the same requirements, illustrating how the corresponding rules can be designed. However, this is no more than an indication of requirements given the complexity of technical details and of the different design choices of system operators in the different countries.

The technical requirements presented are discussed as follows: 'Description and background' provides a brief overview of the objective of the requirement and why in general it is needed. 'Scope of relevance' discusses when and where the requirement is especially relevant, and considers the particular power system, VRE share, generator technology, voltage level and other features. 'Implementation in grid codes' refers to real examples to be found in existing VRE grid codes. Since requirements may need to be attuned to the needs of a given power system, 'Adaptation to power system' provides a brief overview of the necessary steps to be taken. Where possible, hints are provided on how to determine appropriate parameter values for a particular system.

A.1 OPERATION RANGES OF VOLTAGE AND FREQUENCY

DESCRIPTION AND BACKGROUND

Customers connected to electrical power systems are provided with alternating voltage of standardised magnitude and frequency. In reality, voltage always deviates from this ideal, which can never be attained exactly due to the physical properties of the grid and its generators. All equipment is therefore able to operate within some tolerance around the nominal values. However, greater deviation can cause equipment faults or permanent damage.

SCOPE OF RELEVANCE

Voltage and frequency operation ranges in general are relevant for all power systems regardless of their size and VRE penetration. The actual voltage ranges may differ between voltage levels, whereas the frequency range is usually the same within all voltage levels of a power system.

IMPLEMENTATION IN GRID CODES

A typical voltage tolerance band for unrestricted generator operation is ±10 % of the nominal value. At high voltage levels, asymmetric thresholds are often given to account for operator practices like operating slightly above the nominal voltage value most of the time to reduce losses.

The frequency tolerance is usually around ±2 % in large interconnected systems. The required range incorporates a safety margin around the frequency range that can be maintained by the system's frequency control scheme in case of particular large disturbances. In smaller systems or island systems, slightly larger frequency bands are required because frequency control is harder to handle in smaller systems.

Outside the given tolerance range, generators must remain operational for a minimum interval of time or may disconnect immediately depending on the magnitude of the disturbance. For example, the European continental system frequency tolerance band is 49.0-51.0 Hz while the range for disturbed operation extends to 47.5 Hz and 51.5 Hz. Generators should remain connected and functional during disturbed operation for 30 minutes. The specified time interval provides an additional safety margin for the system operator to respond to disturbances (ENTSO-E, n.d.).

An example of such requirements from the German transmission grid code is given in Figure 14. Table 8 and Table 9 provide an overview of frequency ranges and voltage ranges for normal and disturbed operation in island power systems within various countries. These differ significantly in size. The power system size is typically the most significant factor when choosing appropriate limits; the VRE share is not necessarily significant and is omitted from the tables provided at (IRENA, forthcoming).

Figure 14: Ranges of operation and required power output for generators from TC 2007 (Germany) (VDN - Verband der Netzbetreiber – e.V. beim VDEW, 2007)

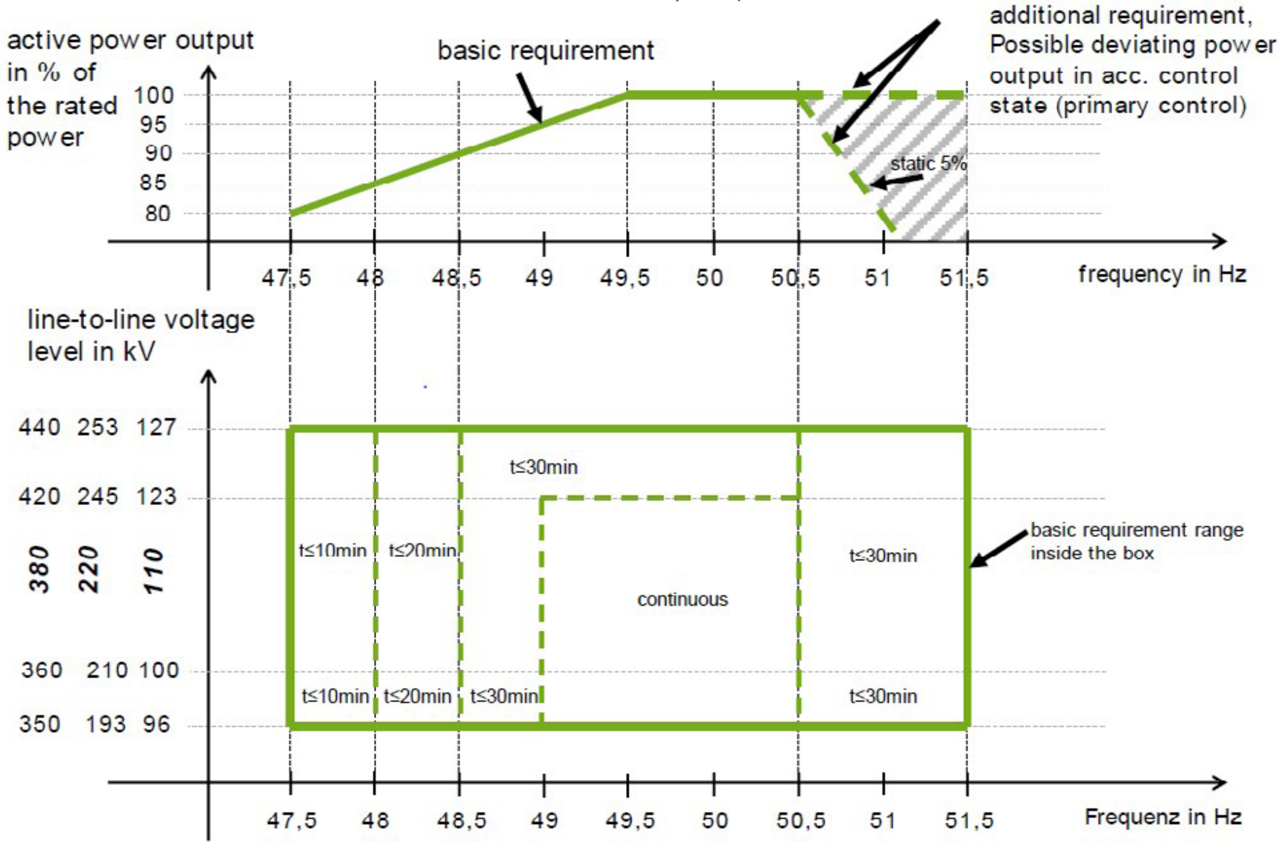


Table 8: Transmission system frequencies in normal and abnormal conditions.

Grid code	Frequency in normal conditions (Hz)	Frequency in abnormal conditions (Hz)
Great Britain	49.5 - 50.5	47.0 - 52.0
Ireland	49.8 - 50.2	47.0 - 52.0
Madeira	49.5 - 50.5	-
Malta	49.5 - 50.5 during 99.5% of a year	49.5 - 50.5 during 99.5% of a year
Greece	49.0 - 51.0 during 95 % of a week	42.5 - 57.5 during 100 % of a week
Canary Islands	49.85- 50.15 for t < 5 min: 49.75 - 50.25	
New Zealand	49.5 - 50.5	47.0 - 52.0

Table 9: Voltages for normal and abnormal conditions.

<table>
<tr><th>Grid code</th><th>Voltage
normal conditions in pu</th><th>Voltage
under-fault conditions in pu</th></tr>
<tr><td>Great Britain</td><td>400 kV: 0.95 - 1.05
400 kV: min. and max. voltage:
+/- 10 %,
but between +5% and +10 %
t < 15min
275, 132 kV: 0.9 - 1.1</td><td>-</td></tr>
<tr><td>Ireland</td><td>400 kV: 0.93 - 1.03
220, 110 kV: 0.95 - 1.09</td><td>400 kV: 0.89 - 1.05
220 kV: 0.91 - 1.11
110 kV: 0.9 - 1.12</td></tr>
<tr><td>Iceland</td><td>220, 132, 66, 33 kV: 0.91 - 1.05</td><td>-</td></tr>
<tr><td>Madeira</td><td>60, 30, 6.6 kV: 0.9 - 1.1</td><td>60, 30, 6.6 kV: t ≤ 20 min for 1.2,
t ≤ 10 min for 1.3</td></tr>
<tr><td>Malta</td><td>132 kV: 0.94 - 1.06
33 kV: 0.9 - 1.05
11 kV: 0.95 - 1.05
400 V: 0.9 - 1.1</td><td>-</td></tr>
<tr><td>Greece</td><td>150, 66 kV: 0.95 - 1.08
20 kV: 0.9 - 1.1</td><td>-</td></tr>
<tr><td>Canary Islands</td><td>220 kV: 0.95 - 1.11
132 kV: 0.95 - 1.10
66 kV: 0.94 - 1.09</td><td><table><tr><td></td><td>N-1</td><td>N-2</td></tr><tr><td>220 kV</td><td>0.93 - 1.11</td><td>0.9 - 1.11</td></tr><tr><td>132 kV</td><td>0.93 - 1.1</td><td>0.9 - 1.1</td></tr><tr><td>66 kV</td><td>0.91 - 1.09</td><td>0.85 - 1.09</td></tr></table></td></tr>
<tr><td>New Zealand</td><td>220, 110 kV: 0.9 – 1.1
66, 50 kV: 0.95 – 1.05</td><td>-</td></tr>
<tr><td>Tasmania</td><td>220, 132, 110 kV: 0.9- 1.1</td><td>220, 132, 110 kV: 0 - 1.3</td></tr>
</table>

ADAPTATION TO POWER SYSTEM

The voltage ranges around the nominal values are usually already specified in existing power systems and do not require further investigation for changing VRE generation shares. Frequency ranges are also likely to exist; otherwise frequency measurements over several months provide insight about the performance of the existing frequency control scheme. However, frequency fluctuations that greatly exceed typical ranges are more an indication that the frequency control scheme needs improvement than a reason for requiring stringent frequency withstand capabilities from new generation assets. Generator equipment availability can become a concern if frequency limits are too wide. IEC 60034 and related standards define typical requirements for rotating electrical machines.

A.2 POWER QUALITY

DESCRIPTION AND BACKGROUND

Ideally, consumers should be supplied with voltages of perfect sinusoidal waveform with a constant amplitude and frequency. Deviations from the desired characteristic can reduce equipment lifetime or even cause physical damage. VRE generators make an impact on the voltage characteristics of a power system in several ways. The most important of these are:

- variation in voltage magnitude
- harmonic content

VARIATIONS IN VOLTAGE MAGNITUDE can be caused by the fluctuation of the power VRE generators feed into the grid. In addition to voltage increases over a longer time period due to high active power feed-in, short, often periodic voltage variations occur known as flicker. In older wind turbine designs, these were caused by unsteady wind speed, for example, as well as turbulences and wind turbine blades passing through the tower shadow. 'Flicker' is the effect of voltage variations, which consumers notice in lighting, for example.

A wave form that resembles a perfect sine wave as closely as possible is an important aspect of grid voltage quality. High harmonic content, which denotes a distortion of the wave form, leads to higher thermal loading and means equipment and consumer devices age prematurely due to the resulting harmonic currents. These also lead to higher thermal loss and sometimes even electronic communication device breakdown. Devices utilising power electronics, including solar PV converters and converter-based wind generators, are major harmonic current emitters. High VRE penetrations thus increase harmonic content in the grid unless specific measures are taken to resolve this.

SCOPE OF RELEVANCE

Voltage variations and waveform distortions are primarily local phenomena. This means power quality requirements for VRE generators are relevant under all circumstances, independent of system size, total VRE share, voltage level or predominant VRE technology. More consumers are affected when more VRE generation capacity is connected in or close to their local distribution system. The impact of individual generators with given characteristics depends on the local strength of the grid.

IMPLEMENTATION IN GRID CODES

In order to restrict voltage magnitude variations, some grid codes limit the frequency of switching operations permissible on VRE units or the magnitude of voltage variation from switching. For example, the German low voltage grid code limits the voltage change caused by switching generator units to 3%. This limit may not be reached more than once in a given 10 minute interval. An approximation formula is provided to calculate the voltage change. A prescribed maximum limits the maximum generator size for a given connection point.

International standards provide definitions of flicker quantification and corresponding limits, such as EN 61000-3-3 and EN 61000-3-11. As an example, they prohibit a 'long-term flicker factor' of more than 0.5 at the worst potential connection point.

Requirements related to harmonic current emissions usually refer to standards describing measurement methods (e.g. EN 61000-4-7) and possibly standards providing limits (e.g. EN 61000-3-2 and EN 61000-3-12). In the German low voltage grid code, maximum relative current amplitude limits are provided for the aggregate of generation units at the same connection point for a wide range of harmonic order numbers. Tables with similar or different values can be found in other grid codes. Harmonic current emission requirements can be met by manufacturers by installing harmonic filters consisting of capacitors and inductors at VRE installations. They can also choose a converter technology that emits fewer harmonic currents in the first place.

ADAPTATION TO A POWER SYSTEM

As power quality requirements do not correspond strictly with system properties, no specific adaptation is needed for a given power system. This means limits can be copied from existing grid codes. Differences between limits denoted in different existing grid codes can be explained more by divergent expert opinion than by technical criteria.

Harmonic current measurement is under discussion because the existing standards do not perhaps sufficiently allow the distinction between equipment emitting or absorbing harmonic currents. Hence, methods and limits provided in existing grid codes may need to be adapted to improve standards in future.

A.3 DEFINED REACTIVE POWER BEHAVIOUR FOR VOLTAGE CONTROL

DESCRIPTION AND BACKGROUND

Reactive power describes a property of devices operating in AC systems, where the equipment can operate in ways either qualified as ‘inductive’ or ‘capacitive’. Reactive power is necessary for building electromagnetic fields around lines and transformers. Characteristics depend on the equipment type, and the asset loading level also plays an important role. Reactive power balancing is essential for voltage control. Consumers, especially those using electric motors, often show inductive behaviour and thus have to be supplied with reactive power from the grid. A device’s inductive reactive behaviour generally decreases the voltage. By contrast, capacitive behaviour increases the voltage. Reactive power in the grid can be provided by switchable capacitors and inductors as well as suitable generators. Synchronous generators are generally able to control their reactive power output, and modern converter-based VRE generators have also acquired this capability. Large industrial consumers in particular are often required to balance their reactive power demand themselves.

Some means of reactive power control capability is desirable for VRE generators for two reasons. Firstly, the power production from VRE generators raises the voltage at the connection point. The ability to influence reactive power behaviour then means higher installed capacities can be connected without exceeding the operational voltage limits. Secondly, as increasing shares of VRE generation displace power production from conventional power plants, sufficient reactive power capability must still be available to maintain stable voltage control in the transmission system.

SCOPE OF RELEVANCE

VRE generator reactive power control capability becomes increasingly important as the share of VRE in the system increases. For converter-based generation, extending the reactive power capability range of the generator systems implies added costs to the manufacturer and thus also the plant owners. The most demanding reactive power capability requirements are therefore placed on units of larger size. Less stringent demands are made of smaller-scale units. Besides distinguishing by unit size, it is also customary to distinguish by the voltage level expected as a result of generator connection. There is no need to distinguish by VRE generation technology, i.e. wind or PV.

IMPLEMENTATION IN GRID CODES

The simplest example of a reactive power requirement found in grid codes is the requested ability to work with a constant power factor. This can be determined by the system operator within a range stipulated in the grid code. With increasing unit size and/or voltage level, requirements are expanded. They demand wider operating areas (capability curves), the ability to change reactive power output depending on voltage or active power output, or even to make the reactive power set point available for remote control by the system operator.

Capability diagrams illustrating a requirement for offshore wind turbines are depicted in Figure 15. Grid codes sometimes also contain a related requirement for entire generation plants consisting of many wind turbines. Figure 16 shows that the plants’ required reactive power range as needed by the system operator may depend on the voltage at the point of connection. Similar figures can be found in many grid codes.

Figure 15: Required reactive power characteristics of wind turbines in different grid codes

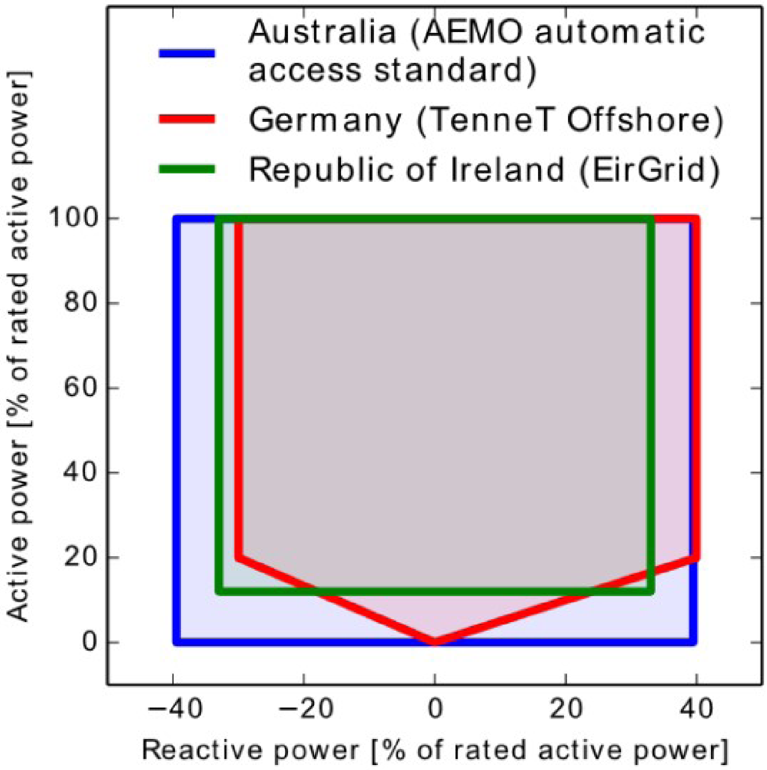
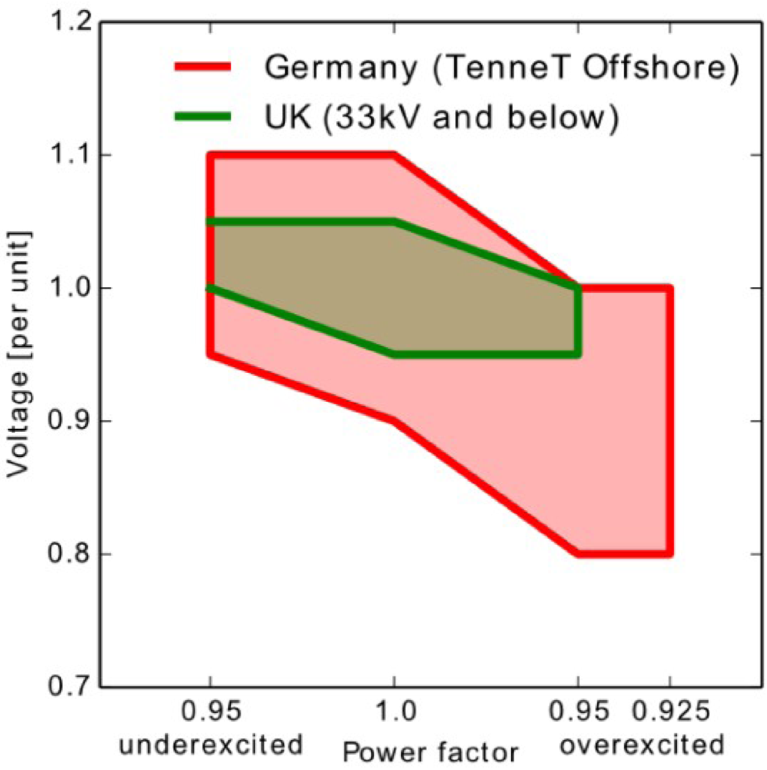


Figure 16: Required reactive power range for offshore wind power plants as specified by German TSO TenneT. (TenneT TSO GmbH, 2012)



ADAPTATION TO A POWER SYSTEM

The reactive power demand of a grid can be assessed by running load flow calculations. For the transmission grid, grid operators regularly carry out such calculations to plan power plant redispatch operations. The required VRE unit and VRE power plant reactive power capability ranges can be determined by performing more extensive load flow studies. These take into account different grid upgrade scenarios, expected VRE generation distribution and the technological capabilities that can reasonably be implemented by VRE generator manufacturers.

Using load flow models of the entire system to assess the necessity for voltage control using reactive power in the lower voltage grids is impractical. These models are not normally available. However, distribution grids are often similar in structure, so that models of the most widely used topologies can be applied instead of modelling the entire distribution grid network.

A.4 FREQUENCY SUPPORT

DESCRIPTION AND BACKGROUND

Electrical energy cannot be stored efficiently in significant quantities, so that generation and consumption must always match within a synchronous electricity system. Grid frequency is the primary signalling mechanism for maintaining the power balance. It rises if generation exceeds demand and falls if there is a lack of generation. Frequencies that are too high or too low can physically damage certain types of equipment. The frequency is regulated by bringing generation plants online or offline as needed and dynamically adjusting their power output. Minor deviations from the nominal frequency are normal and accepted because generators cannot quickly respond to demand changes on every single occasion. System operators maintain operating reserves to ensure that sudden imbalances can be balanced out quickly enough to prevent the frequency from exceeding the required limits. This situation can occur, for example, when a large power plant is disconnected as a result of technical problems. Power reserves are classified according to the time scale in which they are supposed to act.

Until recently, frequency control and load balancing (power reserve dispatch) in the grid have been exclusively provided by conventional generation. VRE generators have been treated as variable negative loads. As VRE penetration rises, reserve power has to be provided by a decreasing number of conventional units. If VRE cannot provide reserve power, system-wide instantaneous VRE penetration and thus overall VRE production are restricted to a level that may be lower than desired in the long term. In Germany, around 15 GW of minimum conventional generation is needed to cover reserve power requirements, which will at times of low load limit VRE penetration to around 60 %. This level had already been reached in 2014 during low load and high VRE feed-in.

SCOPE OF RELEVANCE

The contribution of VRE to frequency control and power reserves becomes useful once the maximum expectable instantaneous VRE penetration approaches levels so high that only little conventional generation needs to be connected to the system. This signifies a point where the desired reserve margins cannot be maintained any longer. Frequency control requirements in grid codes therefore vary with system size and generator portfolio.

In a large interconnected system like the continental European grid, reserve power provision is shared between several countries. Reserve power can be imported and exported if the system is well interconnected, leading to less stringent requirements for generators. Synchronously independent grids usually allow greater frequency ranges, especially island grids. In principle, though, island systems face the same choice between limiting maximum instantaneous VRE penetration to a certain level and requiring frequency control/reserve power capabilities from VRE generation. Frequency control is a system-wide issue, so it is independent from the voltage level.

IMPLEMENTATION IN GRID CODES

Grid codes set requirements for certain generators. However, the actual reserve power is usually procured through a reserve power market, which may limit the VRE reserve power deployment (see section 6.1: 'Reactive power and voltage control').

To provide reserve power, VRE generators must be able reduce their power output if needed to balance excess generation. They need to continuously operate below maximum possible output in order to address excess load or loss of generation. One variant of this reduced output mode of operation is known as delta control capability. This is required by the Danish grid code for offshore wind power plants.

Units that do not take part in active frequency control and reserve provision are still often required to reduce their output power if the frequency rises too much. Generators may also not immediately disconnect from the grid and must not reduce their active power output when frequency drops.

ADAPTATION TO A POWER SYSTEM

Reduced output modes such as delta control lead to a perpetual loss of VRE energy that would otherwise be produced. This means VRE power is sacrificed for the sake of system security. This is only desirable if the VRE share in the system is so high that conventional sources cannot guarantee system stability, and a few per cent of lost VRE power is acceptable. On the other hand, many regulatory and economic questions may need to be addressed.

Power output has to be reduced gradually when it exceeds nominal frequency. If the stipulated power reduction gradient is too low, it may not contribute sufficiently to the prevention of over-frequency limit violation. If it is too steep it may prevent the main balancing mechanisms from working as intended. If in doubt, a power reduction ratio similar to the German transmission code 2007 requirement may be a safe choice.

A.5 FAULT BEHAVIOUR

DESCRIPTION AND BACKGROUND

Faults in a power system include line interruptions or short circuits on transformers, cables or overhead lines. Short circuits cause very high currents which create physical damage on equipment within a very short time. Grid assets are therefore protected by relays that aim to detect dangerous currents and switch off the asset before damage occurs. To prevent unnecessary consumer outages, these switches need to be co-ordinated. Ideally, only the faulty asset will be switched off - or at least a minimal section of the system.

High currents during short circuits arise from generators in the system. The faulty elements therefore have to be disconnected before the generators are damaged. The generators themselves have to remain connected during the incident so that effective fault detection is not compromised. Protective equipment aims to switch off a short-circuited line or transformer as quickly as possible, ideally within around a tenth of a second. Switchgear properties prevent the reaction from being any quicker. Generators also need to remain connected after the incident so that the power balance in the system is maintained once the fault is cleared.

In a power system with a negligible share of VRE generation, it seems desirable that this never interferes with fault detection and can thus be disconnected as soon as a fault is detected. Converter-based VRE generator technology is not able to provide similar levels of short circuit current to conventional power plant synchronous generators. The initial requirement, therefore, was to disconnect VRE generators from the grid as soon as a fault occurs. This is an easy measure to take, and provides effective protection against unintentional islanding. However, it causes major problems once the VRE share increases.

A fault can then cause major generation loss, especially where there is high instantaneous VRE penetration. Studies conducted in 2003-2005 revealed severe problems in North Germany during fault simulations (Quitmann & Erdmann, 2013) (dena, 2005) (Pöller, 2011). Wind turbine disconnection during grid faults would in some cases have led to the loss of more generation than the European primary operating reserve can handle. Similar studies conducted in Denmark showed the loss of large offshore wind power plants during fault incidents was considered a threat to grid stability. This has prompted LVRT (also known as Fault Ride Through –FRT-) requirements for VRE generators rather like those imposed on conventional power plants.

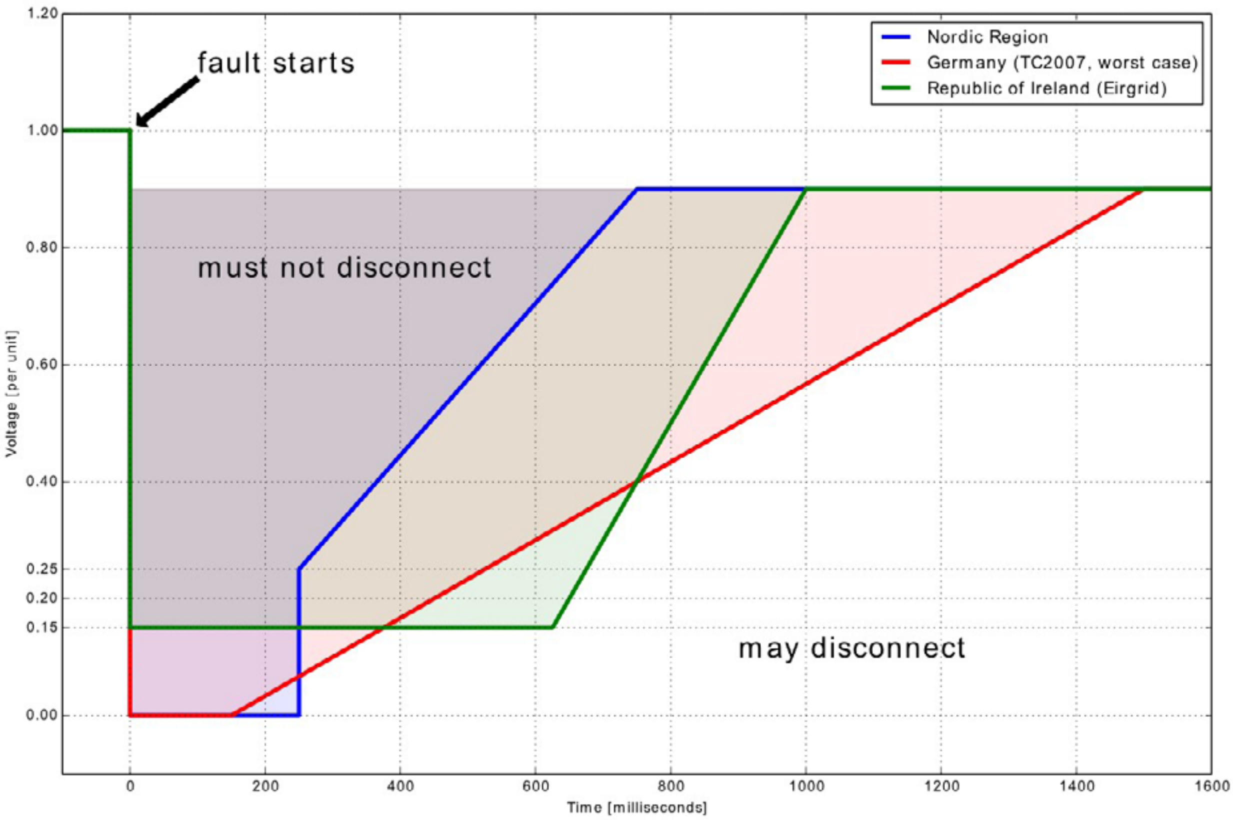
SCOPE OF RELEVANCE

LVRT requirements become necessary when the VRE share rises because a short circuit on one line might otherwise trip enough generators to cause serious frequency deviation. It is first needed at the voltage level where the highest power capacities are connected to single connection points. LVRT was first required from large wind power plants connected to the high voltage grid. When the VRE share increased further, several countries (Germany, Denmark, Ireland) extended these requirements to parts of the distribution grid because the bulk of wind generators is connected to the medium voltage grid. There are at present no LVRT requirements for generators connected to the low voltage grid. However, this is under consideration in Germany, where a large amount of PV generation s connected to the low voltage grid. The actual requirements may also depend on the generator type.

IMPLEMENTATION IN GRID CODES

LVRT requires VRE generators to stay online for a certain time during voltage dips so as to prevent an excessive loss of generation and a subsequent drop of system frequency. The length of time before the unit is allowed to disconnect if voltage is not restored depends on the magnitude of the initial voltage sag. Voltage sags are measured at the point of common coupling of a wind power plant or at the terminal of each generator, depending on the grid code. Different requirements may apply depending on the type of fault and protection systems used in the grid. Time-voltage diagrams ('LVRT envelopes') are used to describe the exact conditions permitting or prohibiting disconnection. LVRT envelope examples from different grid codes are depicted in Figure 17.

Figure 17: LVRT envelopes from different grid codes



The most representative parameters of these LVRT envelopes are as follows:

- voltage minimum
- time to remain connected at the voltage minimum
- post-fault minimum steady-state voltage
- time that voltage may take to recover to this value without triggering generator disconnection

Table 10 provides examples of these parameter values from several island system grid codes.

Table 10: LVRT requirements of island grid pu of nominal voltage.

Grid code	Specification	During Fault		Fault Clearance	
		V_{ret}	t_c in s	V_{min}	t_{max} in s
Canary Islands	Wind power plants	0.0	0.5	0.8	1
Great Britain	Onshore	0.0	< 0.14	0.9	0.5
		0.15	> 0.14	0.8	1.2
	Offshore	0.15	< 0.14	0.94	0.5
		0.15	> 0.14	0.8	1.2
Ireland	400, 220, 110 kV – System: Vret = 0.05 pu	0.05	0.15	1	0.15
	400, 220, 110 kV – System: Vret = 0.5 pu	0.5	0.45	1	0.45
	Wind power plants	0.15	0.625	0.9	3
New Zealand	-	0.0	0.2	0.6	1
Tasmania	-	0.0	0.22	0.9	3

In addition to the requirement to remain connected, some grid codes require VRE generators to provide reactive current during a fault. This limits the spread of voltage collapse to other regions of the network. While converter-based VRE generators provide lower short circuit currents than synchronous machines, they are in general still able to inject up to their nominal current. Grid codes then specify a current contribution dependent on the depth of the voltage dip.

ADAPTATION TO A POWER SYSTEM

LVRT rules should be put in place before the VRE share rises to significant levels. The shapes of required LVRT envelopes represent a compromise involving technology choice and implementation cost that must satisfy the needs of the fault protection scheme in a given system. Optimal system requirement tuning implies carrying out detailed dynamic studies using accurately validated models. Such a procedure may be too costly for smaller systems, while verification of LVRT compliance often requires major effort. In such cases an acceptable compromise may be to adopt existing LVRT requirements from a larger system and build on certification in order to assume compliance.

A.6 ACTIVE POWER GRADIENT LIMITATIONS

DESCRIPTION AND BACKGROUND

In power systems where VRE generation enjoys priority feed-in, conventional generators have to balance out the fluctuations of both load and VRE feed-in. However, most conventional power plants can only change their active power output at a limited rate. Possible gradients range from of 0.5 % of rated power per minute in slow baseload units to up to 20 % per minute in fast-ramping gas turbine installations (Schierhorn, et al., 2014). Very few hydroelectric power plants can ramp from zero to full output within a few seconds (Shapiro, 2011). Where there is a high share of VRE generation, it may be necessary to constrain the priority feed-in scheme by limiting the power gradients allowed to VRE generators. This means the residual load can more easily be covered by the less flexible conventional generation. (Schierhorn, et al., 2014).

Limiting the rate of active VRE generator power increase is relatively easy to implement, simply by reducing the active power output compared to the maximum possible output if it rises too quickly. On the other hand, limiting the rate of active power decrease caused by a decline in primary power is more challenging. Retaining the active power output is hardly possible if the wind stops blowing or the sun stops shining. Limiting the decrease rate may only be possible if the VRE generator is already running at reduced power output. Otherwise storage devices like batteries and supercapacitors would need to be used to limit the downward gradient.

SCOPE OF RELEVANCE

Active power gradients are a system-wide issue depending on the overall VRE penetration and the abilities of the conventional generator portfolio. The necessity to limit gradients is thus in principle independent of voltage level and generator size. It is, however, highly dependent on the distribution of VRE generators. This is because smoothing effects, especially relating to primary energy availability, are less prominent if a high number of generators are installed in a small area.

IMPLEMENTATION IN GRID CODES

Active power gradient limits are only in place in a few countries for wind turbines. The rules focus on the behaviour of wind turbines once the cut-off wind velocity is reached. They set limits on how fast wind power plants may ramp down from rated power. Such requirements usually only apply to large wind power plants but not to single turbines.

The Danish grid code for wind power plants connected to the high voltage grid sets no specific constraint on active power gradients. However, it requires generators to be able to constrain their ramp rate if this is demanded by the grid operator.

Other grid code power gradient limits refer to ramps when generators are reconnected to the grid after a fault. If a generator is tripped due to a grid fault or frequency deviation, its active power ramp rate can be limited when it is brought back online. This rule is in place for all VRE power plants connected to the German transmission grid, and they are allowed to come back online with at least 10 % but no more than 20 % of rated power per minute. (VDEW, 2007) (BDEW, 2008)

ADAPTATION TO A POWER SYSTEM

Active power gradient limitations for VRE generators are needed once there is a significant VRE share. Actual limits to be imposed in grid codes involve ramping studies. These take into account the ramping capabilities of the conventional generation park, present and planned VRE share, regional VRE generator distribution and potential spatial effects of weather phenomena.

A.7 SIMULATION MODEL

DESCRIPTION AND BACKGROUND

Simulating possible scenarios concerning switching states (network topology), load and generation dispatch plays an important role in power system planning and operation. Grid operators often use computer simulations to predict the behaviour of their grid, especially the transitory behaviour during faults or extreme situations. The operator has to know the properties and behaviour of the generators in its grid to get representative results from its model. Generator owners are thus often required by the system operator to hand in simulation models in a specified format before they are allowed to connect their unit to the grid. With VRE generation share increasing, it becomes more and more important to include validated VRE generator models in this requirement as well as demand models from the largest conventional power plants.

SCOPE OF RELEVANCE

The requirement to provide generation asset simulation models depends both on the total VRE share in the system and on the size of the VRE generation units. Large installations like offshore wind power plants make a significant impact on the grid even if their total share of energy is still low. On the other hand, large numbers of small VRE plants in the distribution system also make a major impact on system behaviour. The size of generation units generally correlates with the voltage level to which they are connected. This means grid codes usually demand simulation models first for power plants connected to the high voltage transmission system. Lower voltage levels usually follow when the amount of connected generation reaches significant levels. Dynamic models for generators connected to the low voltage systems are practically never required since modelling and simulation represent too much effort to be feasible for low voltage system operation.

IMPLEMENTATION IN GRID CODES

Grid codes commonly specify the format, quality and level of detail of the required simulation model. Some system operators may allow aggregated models for sufficiently large wind or solar parks with a point of common coupling. Others may require separate models for each wind turbine or PV unit. A manufacturer declaration or a third party certification for the model may also be required (see section 6.4: 'Generator compliance '). For example, the Danish grid code documents demand a simulation model from wind power plants with more than 50 KW capacity (Energinet.dk, 2015). In Germany, power plants connected to the medium voltage level are required to prove grid code compliance either by means of tests or through simulations using validated models. (BDEW, 2008) Compliance has to be certified by an independent body. Failure to provide a certificate will result in grid access being denied.

Grid codes can refer to international standards for simulation models. For example, the IEC 61400-27 standard specifies electrical simulation models for wind turbines.

ADAPTATION TO A POWER SYSTEM

The necessity and design of a simulation model requirement very much depend on established system operator practices. In general, simulation model requirements are recommended when the largest VRE power plants approach the common size of conventional power plants or when the VRE share in the system reaches significant levels. Functions to be modelled include stability (behaviour during voltage dips and response to frequency deviations), active power and reactive power capability, and protection.

A.8 ACTIVE POWER MANAGEMENT

DESCRIPTION AND BACKGROUND

A key task of power system operation is to balance load and generation by allocating the corresponding resources in sufficient quantity on the power markets. The final power plant dispatch also takes into account grid stability requirements as well as transmission capacity limits. To conduct this task effectively and manage the active power resources in systems with increasing VRE generation, VRE generators have to be accessible to active power management.

Since VRE generator power injection primarily depends on wind availability and solar radiation, its manageability differs greatly from conventional generator systems. Once they are feeding power into the grid, the latter can usually be operated with varying flexibility between their rated power output and a minimum operating level. On the other hand, VRE generators depend on external conditions for the availability of output power and have practically no minimum operating level. VRE generation is thus made accessible to power plant dispatch mechanisms by communicating maximum output levels. The generators then limit their power output accordingly at the times when sufficient resources for higher output are available. To make up for reduced power injection, operators need to allocate further resources elsewhere.

Active VRE generator power management is desirable even in power markets with VRE priority dispatch because they can then contribute to managing grid congestion and stability issues. Systems with a significant VRE share therefore require VRE generators to have active power management capabilities.

Where a very high VRE share is reached, VRE generation may also exceed demand. If excess power cannot be exported, VRE generators have to be curtailed to maintain power balance. This may be the case even before VRE generation exceeds the load. This is because a certain number of conventional power plants usually have to stay online to provide ancillary services and balance out fluctuations in the VRE generation. Often they cannot operate below a particular minimum loading limit.

SCOPE OF RELEVANCE

All VRE generators may be expected to have the ability to curtail power output regardless of size and voltage level. This depends on overall VRE penetration and local grid capacity. Where there is a low VRE share, active VRE generator power management capabilities are not necessarily needed. On the other hand, the ability to dynamically restrict VRE generation power output becomes indispensable for system operation at any significant VRE share level.

IMPLEMENTATION IN GRID CODES

In Germany, PV generators with less than 30 KW capacity that cannot be controlled remotely have to limit their output to 70 % of rated power. All other VRE generation must be able to reduce power output at the request of the system operator (VDE, 2011). Temporary curtailment for system management reasons is associated with full financial compensation for the energy not fed into the grid. This ensures there is no obstruction affecting incentives to install further VRE capacity. However, it also means using elaborate measurement and calculation schemes to estimate the corresponding amount of energy.

The German BDEW Medium Voltage Guidelines stipulate step-by-step power reduction capabilities of at most 10% of rated power output. The output levels of 100%, 60%, 30% and 0% of rated power output are given as examples for common use. Other grid codes do not restrict the requirement to a limited number of predefined output levels but request any proportion at 0-100% to be provided to the system operators.

ADAPTATION TO A POWER SYSTEM

VRE generator technical capabilities for active power management should be required at any VRE penetration level. Whether an output level percentage is desired or a limited number of predefined steps varies according to ease of implementation, generator size or voltage level.

In addition to active power management for congestion management purposes, detailed stability studies are necessary. These evaluate how much essential conventional generation capacity is needed to ensure system stability. This takes into account the existing and planned VRE generation share and the technical capabilities of the units installed.

A.9 COMMUNICATION

DESCRIPTION AND BACKGROUND

Power system operation requires communication in several ways, especially in the transmission system. Transmission of real-time measurement data is necessary to assess system state and identify advantageous operational measures. The desired state of switching equipment, compensation and generator power must be communicated to the corresponding actors. As VRE generation replaces conventional generation that could be controlled by system operators, it is vital that VRE units gain the communication features necessary for state assessment and controllability. The need for communication increases with as the VRE share rises, since the higher power flow variability corresponds to a greater variance in possible system states.

A wide range of standards and solutions specific to particular manufacturers have been developed for communication equipment and protocols. Recent attempts to unify the power system communication landscape are converging in IEC 61850.

SCOPE OF RELEVANCE

The necessity for VRE generator communication capabilities rises with VRE share. Given the accompanying cost, it is useful to require communication access first for units above a certain power rating. However, since the majority of units will need to be accessed where there is a high VRE share, it is a good idea to set a low threshold above which communication is required. Communication is necessary for implementing other common grid code requirements. This is especially the case for VRE generation management via curtailment, reserve management for frequency control, gradient limitations and voltage control support via access to reactive power set points.

IMPLEMENTATION IN GRID CODES

Many grid codes do not enforce a specific communication interface but allow the VRE generator owner and system operator to agree on a common solution. Other grid codes require a single communication protocol. The Italian grid code stipulates use of IEC 61850 for all generators. (Terna Trasmissione Elettricità Rete Nazionale S.p.A, 2004)

ADAPTATION TO A POWER SYSTEM

All generators with a power rating of more than a few kilowatts should feature a communication interface. Unless a power system operator has already decided on a specific communication solution, it is recommended that IEC 61850 be selected as standard communication protocol.

A.10 PROTECTION

DESCRIPTION AND BACKGROUND

Reliable power system operation builds on the awareness that equipment failure will occur and the careful implementation of strategies that mitigate the impact of faults. The most reliable power systems contain a safety net with several layers of protection and can identify and isolate faults quickly and with minimal impact on the remaining system. Generators must possess a certain level of resilience against faults in the grid. However, they also need to be equipped with protective devices that can disconnect the generator before permanent damage is done.

VRE generator protection must be compatible with grid code requirements for fault behaviour like LVRT or low frequency ride through. For example, generators have to stay connected during brief voltage dips but should then disconnect during permanent faults.

With high VRE capacities installed in distribution grids, it load and generation can approximately match when a distribution system is disconnected from the transmission system. This is called unintentional islanding and may pose a safety risk to consumers and operator personnel if not detected. Protective equipment also aims to identify such situations and disconnect the generator accordingly.

SCOPE OF RELEVANCE

Effective generator protection is essential for all generators, including those running VRE plants.

IMPLEMENTATION IN GRID CODES

Grid codes commonly specify settings or recommended ranges for standard types of protective relays. Such settings consist of a voltage or frequency threshold and a corresponding time after which the relay must trip. Irregular operating conditions are detected either when the voltage or frequency becomes too low or too high. Some grid codes specify several steps or additional criteria that can be measured at the generator site or at point of connection.

ADAPTATION TO A POWER SYSTEM

Protective settings to be specified in grid codes must be harmonised with the needs of the system operator, who in all cases already runs a protection scheme. Care must be taken to prevent the tripping conditions of protective relays and the LVRT requirements (VRE generator fault behaviour) from interfering with the protection setting.

Annex B: IEC and IEEE standards commonly used in grid connection codes

Table 11: IEC and IEEE standards relevant to power systems and VRE integration.

Standard	Function	Content
IEC 60617	Terminology	Graphical symbols for diagrams
IEC 60034	Product specifications	Rotating electrical machinery
IEC 60044	Product specifications	Instrument transformers
IEC 60045	Product specifications	Steam turbines
IEC 60076	Product specifications	Power transformers
IEC 60143	Product specifications	Series capacitors for power systems
IEC 60186	Product specifications	Voltage transformers
IEC 60308	Product specifications	Hydraulic turbines
IEC 60358	Product specifications	Coupling capacitors
IEC 60521	Product specifications	AC watt metres
IEC 60687	Product specifications	Static watt metres
IEC 60905	Product specifications	PV devices
IEC 61194	Product specifications	Characteristic parameters of stand-alone PV systems
IEC 61277	Product specifications	Terrestrial PV systems
IEC 61400	Product specifications	Wind turbine design
IEC 61868	Product specifications	Insulating mineral oils
IEC 62052	Product specifications	Electricity metering equipment
IEEE 1094	Product specifications	Wind farm design and operation
IEEE 112	Product specifications	Induction motors
IEEE 115	Product specifications	Synchronous machines
IEEE 421	Product specifications	Synchronous machines
IEEE 929	Product specifications	Solar PV
IEC 60870	Data, broadcasting, communication	Telecontrol tasks
IEC 62056	Data, broadcasting, communication	Electricity metering exchange
IEC 61970	Data, broadcasting, communication	Energy management system application programme interface
IEC 61724	Data, broadcasting, communication	PV system performance monitoring - guidelines for measurement
IEC 61727	Data, broadcasting, communication	PV systems - characteristics of utility interface
IEC 61850	Data, broadcasting, communication	Communication networks and systems in substations - Part 3: general requirements
IEC 61968	Data, broadcasting, communication	Application integration at electric utilities
IEC 60071	Standard practices	Insulation co-ordination
IEC 60326	Standard practices	Design and use of printed boards

Standard	Function	Content
IEC 61036	Standard practices	AC electricity metering
IEC 61268	Standard practices	Reactive power metering
IEC 61936	Standard practices	Erection of power installations
IEC 62053	Standard practices	AC electricity metering
IEC 62054	Standard practices	Electricity metering
IEC 62305	Standard practices	Protection against lightning
IEEE 142	Standard practices	Grounding in power systems
IEC 61140	Standard practices	Protection against electric shock - common aspects for installation and equipment
IEC 62257	Interconnection	Microgrids
IEC 62786	Interconnection	Distributed energy resources interconnection with the grid (under development)
IEEE 1547	Interconnection	Interconnecting distributed resources with electric power systems

Annex C: Glossary

Term	Description
Active power	The part of alternating current power which can perform work.
Alternating current	Electrical current which changes direction along a power line with periodic frequency (typically 50 or 60 Hz) in a sinusoidal wave.
Ancillary services	Services provided by system actors that may build upon grid code requirements and may or may not be monetarily rewarded (e.g., contributions to voltage and frequency control).
Black-start	The process of energizing an electricity system without any pre-existing electricity supply. Black-start capabilities are necessary for system restoration after blackouts of the entire system.
Curtailment	The reduction of the active power output of a VRE generator below the maximum it could produce in the prevailing conditions (wind, irradiation, temperature, rain etc).
Direct current	Electrical current along a power line which does not change flow direction in steady state.
Distribution system	Electrical power network operating at voltages below transmission system voltage; operated by DSO.
Distribution System Operator	Responsible for operation, maintenance and planning (parts of) the electrical power distribution network. Network operator in charge of the lower voltage levels.
Fault Ride Through	The ability of a generator to stay connected to the grid during a fault. Usually this refers to Low Voltage Ride Through.
Feeder	A distribution network power line that distributes electricity from a connection point with the transmission network to connected electricity consumers.
Feed-in tariff	Conditions of financial return to VRE operators for providing electrical energy to the power system.
Flicker	Variations in voltage magnitude that would cause a light bulb to flicker.
Grid operator	Entity responsible for supervising grid operation including asset management, safety, system balancing and other system services.
Harmonics	Oscillations in the voltage occurring at integer multiples of the system frequency.
High voltage	Voltage level above 100 kV; e.g. 110 kV. Voltage levels above 200 kV are often referred to as extra-high voltage.
Instantaneous penetration	For a particular point in time, the fraction of the electrical load covered by VRE.
Interconnected	This means a region is connected to other regions.
Inverter	Power electronic device to convert DC power to alternating current power.
Low voltage network	Electricity network with nominal voltage below I kV e.g. 110 V, 230 V or 400 V.
Low Voltage FRT	See Low Voltage Ride Through
Low Voltage Ride Through	The ability of a generator to stay connected to the grid when the voltage falls below standard limits during a fault. Often used synonymously with fault ride through.
Medium voltage	Voltage level in the range of tens of kilovolts; e.g. 10 kV, 20 kV or 30 kV.
Network operator	Responsible for operation, planning and maintenance of (a part of) the electrical power network; may be under regulation.
Nominal frequency	The design frequency for the alternating current in a power system. A country's nominal frequency is typically either 50 Hz or 60 Hz. In stable operations, the system frequency should remain close to the nominal frequency.
Nominal voltage	The design voltage for a part of the power network. In stable and secure operations, the system voltage for this part of the network should remain within a set range around the nominal value.
Operating reserve	Reserved active power capacity that can be called upon from operating generators in the case of a power deficit or surplus.

Term	Description
Plant operator	Entity responsible for supervising generator operation.
Point of common coupling	VRE power plant grid connection point that consists of multiple units. Typically this is the transformer which connects such a plant to the grid.
Primary energy	Power source converted by a power plant to produce electricity; e.g. wind, solar radiation, biomass, coal, gas, oil, water.
Primary operating reserve	Operating reserve provided by power plants already connected to the grid and running at reduced power output. Also called primary reserve. The minimum allocated primary operating reserve should be the power of the largest power plant in the system.
Primary power	Primary energy that can be converted by a VRE power plant at a given point in time.
Primary reserve	See primary operating reserve.
Ramping	The change in active power output over a defined period of time.
Ramp rate	The rate at which a generator changes its active power output.
Rate of change of frequency	The rate (measured in Hertz per second) at which the system frequency (measured in Hertz) changes.
Reactive power	The part of the alternating current power responsible for building electromagnetic fields around components; reactive power cannot perform work.
Reversed power flow	Classical distribution systems only connected consumers. The power was therefore supplied via the transformer from the next highest voltage level, and the direction of the power flow was always the same. Connecting numerous small generators next to consumers can mean local generation exceeds local demand, so that the direction of the power flow in the distribution system can be reversed. Power then flows via the transformer to the higher voltage level.
Synchronously independent area	An alternating current power system that regulates its own frequency.
Synthetic inertia	Response of power converter generator relating to acceleration and deceleration on power imbalance, with details to be specified in grid code. The purpose is to imitate to some extent the response of a rotating electrical machine.
System network operator	See network operator
Transmission system	System designed for long-distance electricity transmission; usually operates at hundreds of kilovolts.
Transmission system operator	Responsible for operating the transmission system
Transmission system network operator	See TSO
Unbundling	The separation of transmission and generation infrastructure ownership in the power system. This separation facilitates the introduction of market competition between generators by preventing grid operators from preferring their own generators.
Variable renewable energy	Energy from generators such as wind turbines and solar panels whose power output varies with the weather.
Vertically integrated utility	A utility which owns and operates both transmission and generation infrastructure, possibly also distribution and retail.
Virtual inertia	See synthetic Inertia
Voltage control	The ability of a generator to contribute towards keeping the voltage between regulated limits. Generators contribute to voltage control by adjusting their reactive power output automatically.

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