The Role of Grid Codes for VRE Integration into Power Systems

Development of power system specific requirements

Dr. Thomas Ackermann, Peter-Philipp Schierhorn, Dr.-Ing. Nis Martensen
Energynautics GmbH
Darmstadt, Germany
t.ackermann@energynautics.com

***Abstract*ð Grid connection codes specify minimum requirements that generator systems must fulfill in order to be allowed to connect to the public electricity system. As such, they define sets of features that need to be built into modern generator system such as wind and PV generators (variable renewable energy, VRE). Hence, grid code design plays an important role at the boundary between the requirements of secure system operation and the aim to achieve a cost-efficient energy mix with the highest possible share of VRE.**

Keywords: Grid Code Design; VRE Integration; Technical Requirements, Small Power Systems.

I. INTRODUCTION

The power sector is accelerating its global transition towards a sustainable energy regime. Since 2011, over 100 GW of new capacity added worldwide each year is from renewable energy - more than that of new fossil fuel and new nuclear power 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.* 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%. Analysis published by IRENA also indicates that the global share of VRE can be expected to increase to up to 20% by 2030. [1]

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 are facilitating new operational practices for power systems. These technology 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 the electricity service for consumers continues to be secure while deploying new technologies and adopting new operational practices. All three components: technology, operation and regulation, need to be taken into consideration if VRE is to be successfully integrated into electricity networks. Such rules are set in the grid code, which is published by the grid operator or the utility. It may be legally binding both in that a generator fulfilling grid code requirements has a right to get connected, and that the operator has the right, or even the duty, to reject requests for non-compliant generators. This is not always the case, grid codes may also be only guidelines with some room for negotiation, this depends on local legislation.

Especially for small countries just starting out on VRE integration, the development of a grid code can be challenging. Finding the right balance between requirements that are strict enough to ensure operational security of the system even at much increased VRE shares, but do not create a barrier to investment in renewable energy, can be particularly difficult for countries and areas with little or no experience in the field. In the past, grid operators have in some cases tried to bypass this problem by simply copying grid codes from other countries, completely ignoring the particularities of different systems and creating grid codes unfit for actual use in the process. While this may be the worst possible solution to grid code development, much can indeed be learned by studying grid codes from other countries and by international cooperation between countries with a similar environment and similar challenges. Grid codes must be adjusted to take care of each systemôs needs, but not each and every requirement has to be individualized. For a country with only a small market, a large degree of overlap with the requirements present in larger markets may also make more technology available and drive down investment cost for VRE.

II. POWER SYSTEM SPECIFIC REQUIREMENTS

VRE grid codes can be developed for a grid operatorôs 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 ï peak load and geographical size ï 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 ï 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 high VRE distribution grid feed-in the leading to different issues and the need for transmission grid structures differing from high VRE feed-in.
- 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.
- The state of the art ï 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 ï In other 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. 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.

III. GRID CODE DEVELOPMENT

A. *Importance of adequately strict requirements*

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 countryôs 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.

However, great care must be taken in evaluating the cost and benefit of each requirement set in the grid code. Both too strict and too lenient sets of technical requirements may pose a barrier to large scale VRE integration in the long run. Each requirement leads to an increase in investment cost for VRE generators as additional equipment has to be installed. Overly strict or very unusual requirements can drive investment cost so far that VRE are no longer economically feasible, and very high feed-in tariffs or subsidies are required to increase the VRE share. On the other hand, very lenient requirements decrease investment cost and make it cheaper to install VRE, potentially driving up VRE shares short term. As experience from Germany and Spain shows, large shares of VRE fulfilling only inadequate grid code requirements can lead to operational security issues very quickly, requiring costly retrofits, or even causing blackouts in the worst case.

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 countryôs 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.

Setting up the right scope of requirements is not an easy task and requires detailed analysis of the power system, the existing regulatory and legal framework and the countryôs renewable energy policy. The most important aspects will be discussed in the following sections.

B. *Studies*

Setting the parameters of 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 may be required:

- 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.

C. *Priorisation of requirements*

In a changing power system, the main driver for new requirements for VRE generators is the highest instantaneous penetration to be expected in operation. This parameter is referred to as ôVRE penetrationö in the following prioritisation table (Table 1). In this scale, ôlow VRE penetrationô approximately refers to single digit percentages and œexclusive use of VREô 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.

Once grid code requirements are updated with rising VRE share and/or changing renewable energy policy and targets, units connected before the update usually remain online, only fulfilling the requirements demanded at their time of connection. With this in mind, grid code requirements should always be designed for the highest expected VRE penetration within the lifetime of newly connected units.

TABLE 1: PRIORISATION TABLE.

Power system context	Technical requirements
Always needed	• protection, • power quality, • power reduction during over-frequency
Low VRE penetration	• communication • adjustable reactive power • constraining active power (active power management)
Higher VRE penetration	• LVRT including current contribution • simulation models
Very high VRE penetration	• 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

From experience in several developing countries with small power systems, VRE share and instantaneous penetration can increase very quickly if sufficient incentives are set. The prime example of such a case is the installation of more than 500 MW of utility scale solar PV in the Honduran 1600 MW peak system within less than a year, escalating maximum instantaneous VRE penetration from zero to above 70 % during sunny low load weekends. Especially in small systems, development may happen faster than the grid code can be updated. It is thus advisable to keep an especially close eye on renewable energy policy when designing grid codes for small systems, and to be careful with very lenient requirements. Unfortunately, the impact of too strict requirements is highest in small markets. This issue will be discussed in the next section.

D. *Impact of Technical Requirements in Small Markets*

Small power systems face a special dilemma when developing grid codes. The development cost is high compared to the overall budget of the utility or the system operator, incentives that fuel investor interest can let VRE shares skyrocket within very short time frames, and system stability is more endangered in small than in large systems. While this seems to call for very strict and specific connection requirements, implementation of those can in the worst case completely undermine VRE development.

If a major player in VRE development, in this case meaning a sufficiently large country with VRE experience and a stable incentive system, decides to set stricter or very specific requirements, chances are high that manufacturers will react and offer the required technology so as not to lose the large market. Due to the market size, the price increase will usually be reasonable. The situation will be completely different if completely new requirements are introduced in a small market first. It may not be feasible for manufacturers to develop new technology for a very limited market, or investment cost will drastically increase. Operators of small systems should thus thoroughly analyse technology options already available before setting their requirements.

E. *Grid Code Revision Process*

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.

F. *Ensuring Grid Code 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.

IV. LEARNING FROM INTERNATIONAL EXPERIENCE

For every country, area, grid operator or utility looking to increase VRE shares or faced with political decisions to do so, it is advisable to look at the experience from early adopting countries in Europe. This helps to avoid mistakes that have already been made elsewhere, and will increase the understanding of challenges of VRE integration and possible solutions.

A. *Germany: The 50.2 Hz Problem*

The German œ50.2 Hz problemô serves as an example of what can go wrong if grid code development is not co-ordinated with energy policy. A grid code requirement [2] 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 Hertz (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, thanks to Germany's feed-in-tariff, PV installations grew so fast 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 [3].

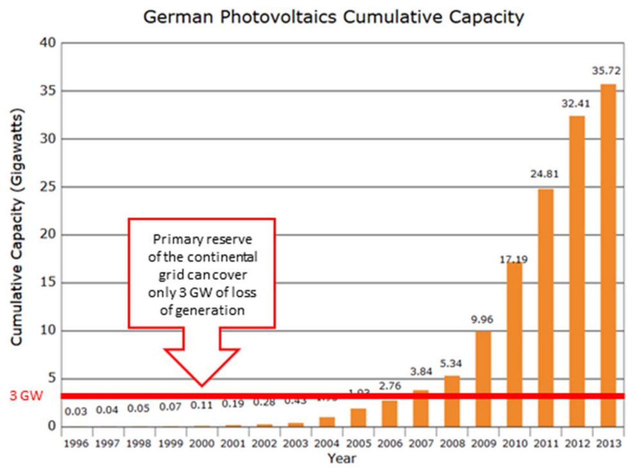

Figure 1: PV capacity in Germany, reaching 43 % of peak load in 2014 and exceeding primary reserve capabilities from 2007 onwards.

The 50.2 Hz problem mainly affected PV generators in Germanyôs low voltage network. In the medium voltage network there is also a legacy of inappropriate grid requirements relating to under-frequency ï ôthe 49.5Hz problemô (affecting primarily wind and cogeneration plants). This was also recently addressed by legislation. 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 sinks. This is because it indicates there is already not enough generation in the system to balance the load.

B. Spain: LVRT Retrofit

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 [4]. 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 ïREE- in Spain and Redes Energéticas Nacionais ïREN- 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 [5]. 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 [6]. 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 [7].

C. Denmark: Early Adoption of Delta Control

Denmark has been a pioneer in the integration of both onshore and offshore wind. In 2014 wind energy generated was equal to 40% of Denmarkôs 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. Delta control functionality is required in the Danish wind grid code [8] 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 ñmust be commenced within two seconds and completed no later than 10 seconds after receipt of an order to change the set pointò. Delta control is usually only provided when the wind feed-in is already high.

D. Bundling of Resources

Some of the challenges faced by operators of small systems described in sections III.C and III.D can be mitigated by pooling regional resources. This may take the shape of a regional, international grid code similar to the Nordic Grid Code used by the Scandinavian countries, but even less formalized cooperation between operators may be very useful. From a technical point of view, small, synchronously interconnected systems directly influence each other much more than larger systems, thus making a coordination between operators on a technical level sensible anyways. This is already often done with regard to area control error, voltage ranges and reactive power flows, but may be extended to the requirements for VRE, especially when it comes to fault behaviour.

But even without interconnection, pooling of resources and harmonization of requirements may give a group of small system operators with similar systems more impact on the market. The cost associated with grid code development and the necessary studies will also be reduced by the utilization of synergies. A good example of regions with operators usually constrained by comparatively low budget and with little market power, but good resources would be the tropical islands around the world. Be it in the Caribbean or in the Pacific, most of these island systems exhibit very similar characteristics ï mainly medium speed diesel based systems with high generation cost which lead governments and utilities to look at VRE as a way to reduce cost.

V. Conclusion

The existence of a grid code that matches the needs of the system is a precondition for successful integration of VRE into any power system. This is widely recognized in the pioneering countries, but has not been learned without any mistakes and shortcomings. Countries and grid operators just starting VRE integration can avoid the pitfalls of grid code development by studying the history of European grid codes, their requirements and the mistakes made in the process.

Setting up adequate grid code requirements for a power system requires a range of power system studies, a good knowledge of the system and some degree of foresight on the future development of VRE. Concerning the latter, history shows that operators have in the past tended to underestimate the speed of VRE development. If the right incentives are set, installed capacities can increase very quickly. It is thus advisable to set requirements in a way that the system can still operate safely at very high shares of VRE.

However, overly strict or unusual grid code requirements can significantly hinder VRE integration, driving up investment cost. The right balance between ñas strict as necessaryò and ñas lenient as possibleò has to be found for every power system, utilizing power system studies and international experience. Especially small operators have to be careful not to set up too demanding requirements, which is a challenge since small systems are inherently less stable and thus call for stricter requirements by definition. While new requirements in large markets can expected to be implemented quickly by the manufacturers and cost increase will be moderate through the economics of scale, countries, operators or regions with only little market power have to be careful not to set requirements for technology that is either very expensive or not even available. In this context, pooling of resources in countries with similar characteristics could facilitate grid code development, increase the impact on the market and drive technology development, and reduce the cost of grid code development for the operators.

VI. Sources

[1] International Renewable Energy Agency, "Scaling Up Variable Renewable Power: The Role of Grid Codes," Irena, Abu Dhabi, 2016.

[2] VDE, ĂDIN VDE 0126,ñ VDE Verlag GmbH, Berlin, 1994 / 2005.

[3] Bundesministerium der Justiz und für Verbraucherschutz, *Verordnung zur Gewährleistung der technischen Sicherheit und Systemstabilität des Elektrizitätsversorgungsnetzes (Systemstabilitätsverordnung - SysStabV)*, Berlin: Bundesanzeiger, 2012.

[4] ENTSO-E, ĂStatistical Factsheet 2014,ñ 2014. [Online]. Available: https://www.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2014_web.pdf. [Zugriff am 24 September 2015].

[5] M. Pöller, ĂModelling of Wind Generation for Fault Level Studies,ñ 2011.

[6] A. Cena Lazaro und J. Gimeno Sarciada, ĂThe Spanish experience in the integration of the electricity from wind power plants into the electrical system,ñ 2008. [Online]. Available: http://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20IVGT/Sub%20Teams/Operation/Paper_126_Cena%20(2-4_Task%20Force).pdf. [Zugriff am 24 September 2015].

[7] J. López, ĂWind Development and Integration Issues and Solutions,ñ Paper presented at the Northwest Wind Integration Forum, Portland, Oregon, July 29ï30 2010. [Online]. Available: http://www.nwcouncil.org/media/4776320/WIF-TWG-072910-Hidalgo-072610.pdf. [Zugriff am 24 September 2015].

[8] Energinet.dk, ĂTechnical regulation 3.2.5 for wind power plants with a power output above 11 kW,ñ 2015. [Online]. Available: http://www.energinet.dk/EN/El/Forskrifter/Technical-regulations/Sider/Regulations-for-grid-connection.aspx. [Zugriff am 24 September 2015].