International Conference on Renewable Energies and Power Quality (ICREPQ'13)
Bilbao (Spain), 20th to 22th March, 2013
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.11, March 2013

Challenges in Future Distribution Grids - A Review

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Abstract. The integration of distributed generation facilities and large loads into the electric grid entails power quality issues. Large scale implementation of renewable and other distributed generation as well as relevant loads like heat pumps into the low and medium voltage grid does not longer allow ignoring the influence of those systems on power quality and stability. Grid codes for different regions started to implement the special requirements introduced by distributed generation. Distributed generation is able to reduce but also to increase issues regarding network loading and stability or power quality. Optimised grid control, generator control as well as demand and supply side management are identified as suitable solutions for an optimised integration into the distribution grid.

Key words
power quality, distribution grid, distributed generation, heat pumps, grid integration

1. Introduction

The reduction of the carbon footprint is a main political goal within Europe and especially Germany. In the energy sector this is reflected in the growth of renewable energies, combined heat and power plants and efficient electric and heating components. [1] Connected to the distribution grid are mainly wind, photovoltaic (PV), (micro) combined heat and power ((µ)CHP), battery and heat pump (HP) systems. Some of these systems, but also loads like energy saving light bulbs, are mostly connected by power electronics which introduce power quality (PQ) issues. [2; 3] Furthermore the distribution grid is designed to distribute electric energy generated by central power plants to the customers. The introduction of distributed generation (DG) causes a number of issues regarding power quality, grid stability and network load. [4; 5; 6; 3] DG can, however, also reduce those issues, if controlled appropriately. [7] The relevant standards regarding power quality and grid stability, issues introduced by DG and loads regarding grid stability, network load and power quality, and possible solutions for the low and medium voltage distribution grid are discussed within this review with focus on Germany.

2. Regulation for Power Quality and Grid Integration

Depending on the country there are different standards that regulate the PQ and the special roles for integration of DG into electrical low and medium voltage distribution grids. The European standard EN 50160 defines the characteristics of the voltage at the point of common coupling (PCC) of grid users in public low-, mid- and high-voltage grids. The given values are the limits that can be expected during normal operation. It defines the characteristics of the voltage regarding frequency, altitude, waveform and balance. The standard distinguishes between continuous phenomena and short sudden events. Continuous phenomena are defined by specific limits, while for short events approximate values are given. Table I shows the different limits defined for continuous phenomena in low and medium voltage grids. Power quality (PQ) considers the deviation of the parameters during grid operation to the defined optimal values. [8]

Table I: DIN EN 50160 regulations for power quality in low and medium voltage grids (continuous phenomena)

Phenomenon	Limit
Frequency	50 Hz ± 1% for 99.5% of time
	50 Hz +4% -6% for 100% of time
Voltage change	±10% of nominal voltage
Flicker	Long-term flicker magnitude $P_{lt} \leq 1$ for 95% in a week-interval
Unbalance	Negative sequence component has to be within 0 to 2% of positive sequence component for 95% of the 10 min mean values in a week-interval
Harmonics	Magnitude within the limits specified in a table stating order and relative voltage amplitude of the harmonics for 95% of the 10 min mean values in a week-interval

Additionally there is a VDE (Association for Electrical, Electronic and Information Technologies) and a BDEW (German Association of Energy and Water Industries) guideline for low and medium voltage grids in Germany that define limits on how much the grid operation is allowed to be influenced by the connection of generators. Table II shows the limits for the connection of DG to the low and medium voltage grid. Additionally these guidelines prescribe requirements on generator functionalities regarding voltage stability and active/reactive power output. Table III shows these requirements. [9; 10]

Table II: Connection restrictions in low and medium voltage grids according to VDE-AR-N 4105 and BDEW technical guideline generators in the medium voltage grid

Phenomenon	Limit LV	Limit MV
Voltage	±3% of voltage without DG	±2% of voltage without DG
Flicker	Long-term flicker magnitude P_{lt}≤0.5 (all generators)	Long-term flicker magnitude P_{lt}≤0.46 (at PCC)
Harmonics	Magnitude within the limits specified in a table stating order and relative voltage amplitude of the harmonics	Magnitude within the limits specified in a table stating order and relative voltage amplitude of the harmonics
Unbalance	$\Delta P_{phases} \leq 4.6$ kVA	-

Table III: VDE-AR-N 4105 and BDEW requirements regarding voltage stability and active/reactive power output

Phenomenon (measure)	Requirement LV	Requirement MV
Voltage (static voltage scheduling)	Generators have to participate in static voltage scheduling if claimed by the grid operator.	Generators have to participate in static voltage scheduling if claimed by the grid operator.
Voltage (dynamic grid support)	-	Dynamic grid support by: - Delayed disconnection (see Figure I) - Reactive power output throughout the failure. - To draw not more reactive power after than before the fault.
Voltage (reactive power output)	Reactive power output according to fixed cosφ or cosφ characteristic, given by the grid operator.	Reactive power output according to fixed cosφ or cosφ characteristic, given by the grid operator.
Grid safety management (active power output)	Reduction of active power output to, or below, a percentage of P_{max} given by grid operator	Reduction of active power output to, or below, a percentage of P_{max} given by grid operator
Frequency (active power output)	No automated disconnection due to frequency deviations between 47.5 and 50 Hz. Modulate output power to a given characteristic (40% P_{max}/Hz) between 50.2 and 51.5 Hz.	Reduction of output power with 40% P_{max}/Hz if frequency rises above 50.2 Hz. Increase only if f≤50.05Hz.

Static voltage scheduling is required for the low as well as the medium voltage grid. Dynamic grid support also known as fault ride through (FRT) is specific for the medium voltage grid. Figure I shows the voltage limit curve above that the generators are not allowed to disconnect from the grid. Active and reactive power modulation has to be performed if claimed by the grid operator. [9; 10]

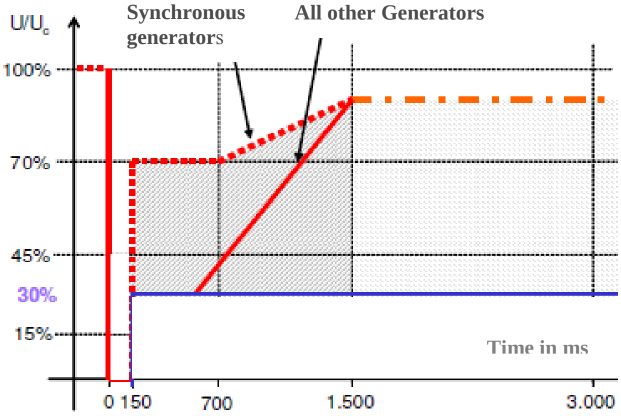

Figure I: Fault ride through voltage limit curve [10]

The specific separation of load and generators in these guidelines leads to unintended consequences, as following example shows. In a distribution grid, where the voltage violates the lower voltage barrier of minus ten percent of nominal voltage (see Table I), distributed generation could help to increase the voltage. However, DG which increases the voltage by more than three percent would violate the VDE guideline. It can be seen that the regulatory boundary conditions do not yet facilitate an integrated approach to more distributed generation and efficient appliances.

The 'Erneuerbare Energien Gesetz' (EEG) ('Renewable Energy Act') is responsible for the development of renewable energy sources in Germany. It encloses further restrictions and technical requirements for the connection of DG. CHP and PV systems with more than 30 kW for example have to offer the possibility to regulate the active power remotely by the local grid operator. [11] These specifications, the VDE regulations and the EN 50160 restrictions show that adequate control strategies have to be implemented by generators. Furthermore it is shown below that demand side management (DSM) and supply side management (SSM) is needed to use the full potential of DG in distribution grids.

3. Grid Stability

3.1. Fault Tolerance / Transient Stability

It is important to grid stability that power plants can operate synchronised and stable during and after faults. The idea of transient stability is to survive disturbances and return to balanced operation by recovering voltage and staying in synchronism with the network. Fault ride through on the other hand is the ability to stay in operation during the fault. Till recently distributed generation was not required to be transient stable but intended to disconnect if a fault occurs in order to put central generation in the position to keep the system stable. The massive growth, especially in wind generation, led to a situation, where the disconnection of DG in the medium voltage grid is not acceptable anymore as the loss in generation would destabilise the system. [12] In medium voltage grids, the minimal time generators have to stay connected to the grid in case of a fault is 150 ms according to the BDEW guideline (see Figure I). [10] The inertia provided by big rotating generators stabilises the frequency even during deep voltage depressions and enables long critical clearing times in a network. DG does not have significant inertia and is therefore in danger of loosing synchronism with the grid during a fault. This lowers the critical clearing time significantly. As synchronous induction machines pole-slip in the case of faults, they draw large amount of reactive power. [13] The guideline for dynamic grid support therefore requires the generators to draw not more reactive power than before the fault (see Table III). [10] FRT capabilities are not required for DG in the low voltage grid. [9]

3.2. Short Circuit Power

The power, or current, that is sustained during a short circuit is an important measure for the design of protection equipment. Short circuit currents cause high magnetic forces, high temperatures in equipment, thermal and mechanical impacts of arcing and dangerous touch and step voltages. The lowest possible short circuit power is important to set the right tripping parameters, the highest possible power to choose the right breaking capacity. [14] Regarding the influence on the short circuit power, DG can be divided into synchronous and asynchronous induction machines and generators connected by power electronics. In case of a fault, synchronous generators contribute significantly to the short circuit power which leads to higher demands regarding the protection systems. Asynchronous generators do not contribute to the fault current. [13; 15] The maximum allowed short circuit power is regulated by the VDE and BDEW guidelines examined above. [9; 10] Power electronic equipment limits the maximum current for self protection purposes and therefore does not contribute considerably to the short circuit power. [16; 15] In weak systems, however, it is reported that DG can have an influence on the fault current. [15] Traditionally the protection equipment depends on a certain fault current to detect the fault. If DG is connected, the fault current is sustained partly by DG, installed between fault and protection, and might therefore be invisible to the protection equipment. This scenario is called blinding of protection. If DG sustains a fault in an adjacent feeder and the protection of the DG-feeder trips first, it is called false tripping. In this case, the clearing of the fault is delayed. Furthermore, typical arrangements of fuse and recloser in combination with DG introduce problems with fault detection and unsynchronised reconnection. Solution to these issues range from simple setting modifications to the introduction of measurement based adaptive overcurrent relays. [15] All adaptive and intelligent solutions, however, rely on a communication infrastructure which adds additional complexity and costs. [17]

4. Network Load

The load on cables and lines of German distribution networks will increase during the next years due to the connection of DG. [18] Even though the LV and MV distribution grids are generously dimensioned, the increase in DG will ultimately lead to the grid being at its capacity limit. [19] A study on distribution grids by the German Energy Agency (dena) shows the need for the construction of up to 193.000 km cables and the installation of up to 93.000 MVA additional transformer power in order to enable further growth in renewable energies in Germany till 2030. [20]Reasons for this are that DG, especially solar power, does work simultaneously and the generation/load profiles of the grids do not match. This leads to peak power loads outside the operating limits of the grid. [18] A sensible control strategy of generators as well as DSM and SSM are advised to tap the full potential of load reductions by synchronising demand and generation within the grid. Especially the transformer load can be reduced this way. [6; 7] Further increase in network load can occur when reactive power control is used to regulate the network voltage like shown in chapter 5.6 [21]

The current flow through the equipment, like cables or transformers, causes an internal temperature rise. The thermal resilience defines the maximum load that can be handled by equipment. If exceeding this limit, equipment will fail and power outages have to be expected. It is possible to operate equipment at higher than rated power for a limited time. This shortens the equipment lifetime and occasions costs, as equipment has to be exchanged earlier. [16] Field tests showed, that exemplary transformers are already operated at 148% rated power for up to 2 hours a day. In this case it led to an oil temperature raise of 50°C above ambient temperature, which is considered to cause abnormal loss of lifetime. [22] FACTS (flexible AC transmission system) equipment can be used to coordinate the loading in the grid. FACTS controllers can change line-longitudinal and –lateral impedances, series voltages and lateral currents within the network to control the power flow. Additionally voltage and frequency can be influenced by the same mechanisms. [14]

5. Power Quality

5.1. Harmonics

Harmonics in the power system are no new phenomenon, but have increased in magnitude due to the increasing use of power electronics. [21] DG with power electronic converters like PV systems or wind power systems can have negative impact on the harmonic magnitude within a distribution grid. [23] Passive harmonic filters and active filtering techniques are discussed as remedial solutions. Standards that limit the allowed harmonic disturbances of equipment connected to the grid can be used to prevent their occurrence. Unfortunately they consider only sinusoidal voltage wave forms. In order to evaluate harmonics correctly, the standards have to consider certain voltage harmonics and non linear behaviour as well [2]

5.2. Transients

Transients are mostly caused by lightning. Connecting or disconnecting a considerable amount of power generation to the network, however, can cause transients if large current flows are allowed. Careful design of generators can limit these currents to acceptable magnitudes. [13] Transients can cause overvoltage protection equipment to trip or to be destroyed. [21]

5.3. Flicker

The term flicker refers to a visual effect caused by voltage variations below a certain frequency. These voltage variations cause lighting equipment to flicker. If this flicker is visible to humans, it is classified as relevant flicker according to DIN EN 50160. The exact limits for flicker is define in the standard DIN EN 61000-2-2. [8] Wind power plants and photovoltaic systems have to be tested regarding their flicker influence on the network. Non-fluctuating DG like CHP systems are not expected to have negative influence regarding flicker. [23] Energy saving light bulbs are less sensitive to flicker as they are connected by power electronic converters. Therefore flicker might be less a problem in future. [24]

5.4. Frequency

Most electrical equipment does rely on a stable network frequency. [7] To sustain a stable frequency, generation has to match the load. Currently big rotating generators in power plants impose the frequency to the grid, while DG synchronises to this frequency. Regularly DG disconnects if the frequency drops below 47.5 Hz (see Table III). [10] If DG is disconnected central power plants have to supply more power. If they are not able to provide more power their rotation speed and therefore the network frequency will drop further. Fault ride through can be used to stabilise the frequency in case of failures. [13; 7] Network relevant loads, like heat pumps can depress the frequency if their load exceeds the grids operational limits. In this case supply and demand side management can support the network frequency. [6] If the frequency exceeds 50.2 Hz, DG has to modulate their power in order to reduce the frequency rise. In medium voltage grids they are not allowed to increase their power again, until the frequency drops below 50.05 Hz. [10] PV systems installed before the VDE-AR-N 4105 became effective are recommended to be retrofitted to the new standard, in order to avoid the hard shutdown of a considerable amount of PV generation at 50.2 Hz. [25]

5.5. Unbalance

In optimal operation the voltage sine curves of the three phases differ by 120° exactly and have the same amplitude. Every deviation from that condition is called unbalance. [7] This unbalanced is caused by the single phase connection of loads and generators to the low voltage grid. It can, depending on its severity, have serious negative impacts on transformers, controls, distributed three phase generators and power electronic devices. [7] Small loads and generators have little impact on the systems balance and are regularly compensated by loads or generators connected to another phase somewhere in the distribution network. If, however, a number of smaller generators is connected to the same phase in the network, they can have significant influence. [7] Generators bigger than 4.6 kVA have to be connected to all three phases. For single phase generators the requirements defined by the VDE-AR-N 4105 permit a power difference of up to 4.6 kVA between the phases at PCC. [9] Unbalance can be addressed by a balanced connection of loads and generators. One phase connection of loads and generators should be compensated by the coordinated connection of similar equipment to other phases nearby. [23] To reduce unbalance, single phase storage systems are discussed. [26] Furthermore there are control strategies for three phase inverters that reduce unbalance. [27]

5.6. Voltage

Voltage is, besides frequency, the most important parameter for the operation of electric appliances. In traditional low voltage networks, the transformer provides nominal or slightly higher voltage to ensure the voltage to be within the authorised range at any position within the grid. The connection of DG, however, increases the voltage locally. This may lead to a violation of the upper voltage limit, stated in Table I and Table II. [7] The operation of temperature controlled heat pumps and other big loads, like electric vehicles, introduces the opposite problem. [6] Voltage regulation is the main challenge of DG integration into the low voltage grid, especially at the end of feeders and in rural areas. [6; 28; 4]

The voltage at PCC is influenced locally by the grid impedance and the power flow due to loads and generation. Formula 1 shows the relationship between the voltage rise ΔV at PCC and the generated and absorbed active and reactive power (P and Q) and the impedance of the cable (Z = R + jX) in lightly loaded networks. The power values are positive for generation and negative for consumption. [13]

$$\Delta V = \frac{(P_{generated} + P_{absorbed}) * R + (Q_{generated} + Q_{absorbed}) * X}{V} \quad (1)$$

It can be seen that active power consumption lowers, while active power generation increases the voltage. The same is valid for reactive power. Reactive power is needed for the magnetisation of inductors. The reactive power needed within the network is regularly provided by the big doubly-fed asynchronous induction machines at power plants. The effect of voltage drop due to the consumption of reactive power, however, can be used to deliberately lower the voltage at DG connection points by increasing their reactive power draw. In this context, however, the X/R relation of the network has to be considered. While X/R >> 1 for transmission systems, it is around one or even lower for low voltage distribution systems. [4; 5] Reactive power control in low voltage networks can be seen critical, as high reactive power flow would be necessary in order to lower the voltage considerably. [7; 29] The additional reactive power contributes to the network load and leads to additional costs as shown in chapter 4. [29] Furthermore, active power management, like DSM, SSM and managed storage, can be used to influence the voltage according to formula 1. The drawback of active power management is reduced availability of loads and less power generation of DG. This leads to higher costs and less comfort. [7; 29] Another possibility to keep the voltage within the desired range is to use on-load tap changers (OLTC). Line drop compensation (LDC) can be used to control the OLTC to keep the voltage at a point in the feeder constant. [30] These concepts, however, are limited if generation and loads are concentrated on different feeders, as only the voltage at one position can be controlled. The reduction of voltage due to too high voltage in a generation feeder leads also to a reduction of voltage in a heavily loaded feeder and therefore possibly to a violation of the voltage limits. [31; 29] Figure II shows simulation results for the voltage at the end of a low voltage feeder with and without voltage control mechanisms. It can be seen that the voltage level in times of high PV generation can be lowered significantly by a combination of OLTC and reactive power control. In this case a reduction from 5.5% to 2.5% overvoltage was achieved. [32]

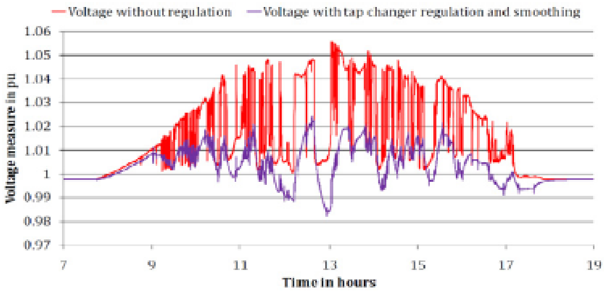

Figure II: Simulated voltage level at the end of a feeder without regulation and with on-load tap changer and reactive power control (smoothing) [32]

In medium voltage grids on-load tap changers and line drop compensation are already used to keep the voltage within the range specified by DIN EN 50160. The reduction or reversal of power flow introduced by DG, however, affects the effectiveness of LDC. Coordination between DG and LDC is therefore required. [30] FACTS equipment like STATCOMs can be used to control the voltage by reactive power control. Static synchronous series compensators (SSSC) can be used to control the power flow and therefore the loading of power lines [14]
Low voltage grids are very rarely equipped with OLTC and LDC. [16; 18] The utility company E.ON, however, is testing an autotransformer for voltage control in feeders with high penetration of PV generators. [33]

6. Integrated Approach to Voltage Stability

As voltage stability is the main issue regarding the integration of DG into the distribution grid an integrated approach to this issue is discussed below. In order to enable the save and stable operation of distribution networks with a high penetration of distributed generation, heat driven loads and electricity storage, an integrated approach to the integration of such appliances is advisable. Figure III shows an overview of different possible approaches to the issue of voltage stability in low voltage networks. The selection of different solutions depends on the local situation. It is, however, important that generators, relevant loads and the grid control are able to cooperate in order to achieve the most cost effective solution.

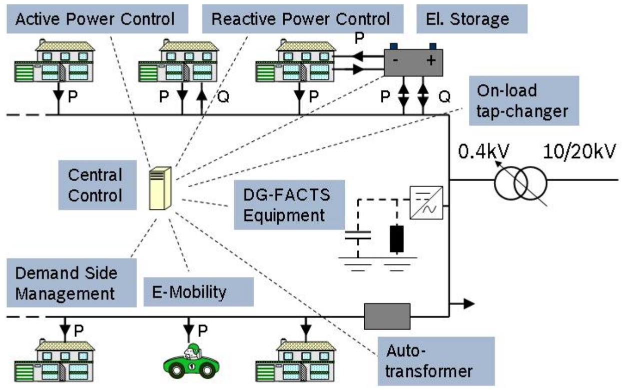

Figure III: Overview of different solution to the voltage issue in low voltage networks

Most inverters already offer the possibility to modify active and reactive power. Corresponding control mechanisms have to be implemented. Energy management systems, implemented on system, house or distribution grid level, need the additional capability to measure or obtain information on the voltage level at PCC and maybe on other sensible locations of the network. Energy management algorithms that are not restricted to purely financial but also grid operation goals should be developed and implemented. [7; 34]
Existing technology of medium and high voltage grids (e.g. FACTS, adapted protection equipment) could be introduced to low voltage networks in order to control the power flow and operate DG, SSM and DSM efficiently. [7] In order to select the most cost efficient approach, the influences of the different measures have to be quantified. The dena study on distribution grids identified the potential of these alternative measures to reduce the need for investment in grid reinforcement by nealy 50%. [20]

7. Conclusions

The integration of DG and relevant loads into the distribution network entails a range of challenges regarding grid stability, power quality and network loading. Currently only generation is considered to fulfil requirements regarding these issues. To ensure save operation, the grid but also DG, relevant loads and storage have to offer additional capabilities. Intelligent operation and design of the grid and generators as well as network oriented supply and demand side management have to be mentioned here. Some of the issues mentioned above can be solved by more than one measure. Financial, technical and regulatory arguments have to be examined to choose the best solution. Further research has to be employed in order to find the exact influences of different equipment as well as operation and management strategies, especially on low voltage networks. Some topics that have to be addressed are: Gaining more knowledge about models; creating new load profiles; developing new power flow calculation methods and methods for network design that incorporate the active role of distribution networks. Furthermore it is advised to put simulation effort into networks that include a range of different systems like PV, µCHP, Batteries and HP, to gain knowledge on their characteristic influences.

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