Power quality: interactions between distributed energy resources, the grid, and other customers

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Abstract: This paper presents the three aspects of power quality concerning distributed energy resources (DER). The voltage quality experienced by a DER unit impacts the performance of the unit: bad voltage quality may reduce the life length of the unit and lead to incorrect operation or tripping. The DER unit's current (the "current quality") impacts the system and through the system other customers. The hosting-capacity concept is proposed as a systematic method for quantifying the impact of DER units. The third aspect of power quality only appears with large (local or global) penetration of DER. The tripping of DER units on voltage dips or frequency swing endangers the reliability, stability and security of the system.

1 Introduction

For a number of reasons a shift is taking place, or expected to take place in future, from large-scale power generation units towards small-scale generation connected to distribution networks. The term "distributed generation" (DG) or "distributed energy resources" (DER) is being used to refer to this small-scale generation. The existing situation is referred to as "centralized generation". Distributed energy resources have advantages over centralized generation in a number of applications, for example cheaper total energy bills in the case of combined-heat-and-power; saving on fossil fuel in case of renewable energy sources, improvement of local reliability in case of weak or unreliable public grids, deferring of distribution system investment in case of heavily-loaded grids, costs security in case of high volatility in electricity prices. [1][2][3][4].

No matter what the application, the integration of sources of electrical energy at distribution level will have impacts on design and operation of the distribution system. A much-discussed impact is the expected deterioration of power quality due to the large-scale deployment of distributed energy resources. On the other hand, the existing power quality may have an adverse effect on the distributed energy resources. This paper presents the relation between power quality and distributed energy in a systematic way. Section 2 reiterates the various aspects of power quality, where the distinction between voltage and current quality is an essential one, and applies this to DER. The three aspects of power quality are discussed in further detail in Sections 3, 4 and 5.

2 Power Quality without and with distributed energy resources

The term power quality refers to the electrical interaction between the electricity grid and its customers or equipment connected to it. A number of different definitions of power quality exist in the literature, but none of them is generally accepted. According to some definitions, only equipment mal-operation is part of power quality, whereas other definitions incorporate
all deviations from an ideal voltage and/or current waveform. The inducing effect due to the presence of current harmonics in overhead lines and cables is in some countries also considered as a power quality phenomenon. Another point of disagreement is whether power quality includes interruptions or not. There is no need at this stage to further add to this discussion. Instead power quality will be considered here as covering all deviations from the ideal voltage and current waveform (a constant-magnitude non-distorted sinewave of nominal frequency and magnitude, with current in phase with the voltage). Interruptions are considered as part of power quality, even though they play a minor part in the remainder of this paper. This viewpoint has been criticized as being far too wide. Power quality would cover almost any aspect of power systems. But this definition has shown its value in that there are no longer any boundary areas and that it allows an integrated study of all aspects that involve the customers.

Power quality concerns the electrical interaction between the network and its customers. It consists of two parts: the voltage quality concerns the way in which the supply voltage impacts equipment; the current quality on the other hand concerns the way in which the equipment current impacts the system [5]. Most of the recent emphasis is on voltage quality, with voltage dips and interruptions being dominant. The underlying philosophy is the view of the power system as in Figure 1. The “customers” may be consumers (“end users”), producers or both. In our case the customers that will be primary considered are the DER units.

![Figure 1. Modern look at electric power systems: network and customers.](image)

When considering distributed energy resources the situations becomes more complex. It makes sense to consider three different power-quality aspects for DER:

1. DER units are affected by the voltage quality in the same way as all other equipment. The impact of voltage disturbances includes a reduction of the lifetime of equipment, erroneous tripping of the equipment and damage to equipment. This issue should be addressed in the same way as for large industrial installations: a sharing of responsibility has to be agreed between the operator of the DER unit and the operator of the grid. An important difference between DER units and other equipment connected to the grid is that the erroneous tripping of DER units may pose a safety risk: the energy flow is interrupted potentially leading to machine overspeed and large overvoltages with electronic equipment.

2. DER units affect the current quality and through the grid also the voltage quality as experienced by other customers. The special character of DER units and their possible wide-scale penetration requires a detailed assessment of this aspect. Below we will
introduce a methodology for assessing the impact of DER on the voltage quality in a systematic way. Also this is not something new. The same problems occur with normal end-user equipment. For example, the large-scale integration of electronics equipment has led to an increase of harmonic levels. Despite that, no systematic study has been done on their impact before a decision was made on the use of this equipment. The situation is different for DER for a number of reasons. The most important difference is probably that the distribution system is not intended for connecting generator sources. It is the task of the network operator to supply its customers with reliable electricity of sufficiently high (or relevant) quality. Generator sources connected to the distribution network may interfere with this task.

3. A third and more indirect aspect of the relation between DER and power quality is that the tripping of a DER unit may have adverse consequences on the system. Especially when large numbers of DER units trip simultaneously, this can have an adverse impact on the reliability and security of the system. Such units have not been designed to contribute to the control and stability of the system. In many cases it is even better that the DER units disconnect from the system as fast as possible during a disturbance. This prevents that the DER units interfere with the existing control and protection systems. With a large penetration of DER such a criterion would lead to severe problems for the system.

The impact of DER on power quality depends to a large extend on the criteria that are considered in the design of the unit. When the design is optimized for energy production only, massive DER penetration will probably adversely impact quality, reliability and security. Several types of interfaces are however capable of improving the power quality. In a deregulated system this will require economic incentives, for example in the form of a well-functioning ancillary services market. The improvement of power quality by means of DER and the structure of a suitable ancillary-services market are discussed in detail in [4].

3 Impact of voltage quality on DER

3.1 Variations and events

Power quality disturbances (voltage disturbances or current disturbances) are deviations from the ideal sinewave that potentially affect the network or the customer equipment. In most studies on power quality a distinction is made between “variations” and “events” (although not always explicitly and not always using this terminology). Variations are small deviations from the sinewave that occur during normal operation. Examples of variations are (harmonic) waveform distortion and voltage (magnitude) variations. Events are large deviations that occur e.g. during switching operations and faults. The distinction between events and variations becomes clearest when considering measurements. Events are those disturbances that require triggering: they are detected when a measurement value exceeds a threshold. For example: a voltage dip is detected by the dropping of the rms voltage below a voltage-dip threshold.

Variations are those disturbances that can be measured at any instant or over any time window. The IEC power-quality measurement standard, IEC 61000-4-30, clearly indicates methods of doing this: starting from a 10-cycle window through aggregated 2-hour values and weekly statistics. This whole procedure assumes that it is possible to exactly predefine the
measurement interval, which is only the case for variations.

3.2 Normal and abnormal events

In design studies it is further appropriate to distinguish between “normal events” and “abnormal events”. Normal events are due to changes in voltage and/or current that are a normal consequence of the operation of a power system. An example is the rapid voltage change due to tap-changer operation. Such rapid voltage changes occur several times a day. Equipment connected to the grid that cannot tolerate these, will suffer a mal-operation several times a day. Therefore all equipment should be immune to these events. Another example of a normal event is the current taken from the grid when a television or computer screen is plugged in. The peak value of this current can be up 50 Ampere or higher, albeit only for a few milliseconds. The fuse or circuit breaker in the supply to domestic customers should be able to tolerate this current. Other equipment connected in the neighbourhood should tolerate the voltage disturbance that results from this current.

Abnormal events are events due to abnormal circumstances, either in the grid or with the customer. A long interruption is the most extreme example, but also a lightning overvoltage or a short-circuit fault fall into this category. It is somewhat difficult to decide about what is normal and what is abnormal. We decided to use the following criterion: switching actions that proceed as planned are normal events; faults and unintended consequences of switching actions are considered as abnormal events. Thus capacitor energizing is a normal event. But re-strike during capacitor de-energizing is an abnormal event.

The immunity of equipment against abnormal events is a matter of trade-off between costs and immunity. The impact of the event is a very important criterion. An example from power-system design is the way in which short-circuit faults are removed. At transmission level the loss of supply to customers is considered as unacceptable, therefore the design is such that a fault does not lead to a supply interruption. At distribution level however, such a design would become too expensive. The consequences of an interruption are also less here because less end-customers are affected. Therefore the design is such that a fault will lead to an interruption for a small number of customers.

For most abnormal events an immunity limit will be chosen. For any event with a severity less than the immunity limit, the equipment should not trip. We will go into more details in this when discussing voltage dips below.

3.3 Voltage quality and DER

The distinction between variations, normal and abnormal events can be used as basis for the design of DER units connected to the grid.

Normal operation; variations

Power-quality variations are the small disturbances in voltage and current as they occur during normal operation of the power system. The design of DER units should be such that existing levels of voltage variations do not lead to premature failure or disconnection of the unit. A higher level of disturbance will typically lead to faster component ageing. A very high
level may lead to immediate disconnection of the DER unit from the grid or even to equipment damage.

For large installations, the local level of variations may be used in the design. Such an approach runs the risk however that the disturbance level increases beyond the design criterion. For smaller, off-the-shelf equipment a global criterion should be used. The design should be such that it can tolerate the disturbance level at any location. The only available guide on this is the European voltage characteristics standard EN 50160. An additional margin has to be considered to cope with the well-known fact that 95% levels are given for most variations instead of 100% levels.

The only variation for which EN 50160 does not give useful values is voltage fluctuation. A long-term flicker severity equal to 1.0 is given as a limit. But this level is exceeded at many locations in the system, as the authors know from experience. The good news is that the fast voltage fluctuations that lead to light flicker rarely have an adverse impact on equipment.

In short, the design of equipment immunity against variations is the same as for any other end-user equipment.

**Normal events**

Normal events are mainly due to switching actions in the power systems or within customer installations. Examples of normal events that may lead to problems with equipment are voltage dips due to motor starting or due to transformer energizing and capacitor energizing transients. It is important that DER units are immune against all normal events to prevent frequent tripping of the installation.

Whereas EN 50160 gives reasonable guidelines for variations, no useful information is available for normal events. The best design rule available is that the equipment should tolerate the worst normal event. Similar design rules are needed for end-user equipment like adjustable-speed drives. The regular tripping of such drives due to capacitor energizing transients (see Figure 2) shows that it is not straightforward to implement these rules.

![Figure 2 Example of a normal event: voltage transient due to capacitor energizing.](image)

Another normal event that may lead to tripping of DER units is transformer energizing. The
second harmonic could be a problem for some equipment (leading to dc current) and it may interfere with some protection and fast control algorithms. An example of a measured voltage dip due to transformer energizing is shown in Figure 3 and Figure 4. The voltage waveform is given for the first few cycles of the dip; the rms voltage and the harmonic components are plotted for the whole duration of the dip. In this case the dip lasted over one second, and the 3:rd and 5:th harmonic distortion was still high about 4 seconds after the switching instant.

The interface between the DER unit and the grid should be designed such that it can tolerate voltage dips due to transformer energizing. The main concern will be the tolerance of power-electronic interfaces against the high levels of even harmonic components.

![Figure 3, Measured voltage dip due to transformer energizing: voltage waveforms (left) and rms voltage versus time (right).](image)

![Figure 4. Harmonic distortion as a function of time for the transformer energizing dip shown in Figure 3.](image)

The design issues are the same with DER units as with end-user equipment, but the consequences of tripping are different. A difference from the viewpoint of the unit operator is that tripping of the unit could pose a safety issue. Tripping implies that the energy flow from the unit to the grid is interrupted immediately. The energy input on the chemical or mechanical side of the unit may take some time to stop. The result is a surplus of energy in the unit that expresses itself in the form of high overvoltages or overspeed in case of rotational machines. Safety measures are obviously needed especially for mass-produced equipment. But as any safety measure has a finite failure risk, the number of trips should be
limited in any case. As normal events may have a high frequency of occurrence, it is of utmost important that the units are immune against these events.

**Abnormal events**
The immunity requirements of DER equipment against abnormal events like frequency swings and voltage dips will depend on the severity of those events. The consequences of abnormal events may be very severe and it is not feasible to design DER units that can cope with any such event. The design should be such that the unit is not damaged, but it may have to be disconnected to prevent damage. In that case the unit will no longer supply electrical energy to the network. This will give a loss of revenue to the operator of the DER.

The loss of a large (conventional) generation unit will lead to a frequency swing in the whole system. The problem is more severe in Scandinavia and in the UK than in continental Europe because of the size of the interconnected systems. The problem is most severe on small islands. Five measured frequency swings are shown in Figure 5; the four on the left were all measured within a one-week period. It is very important that DER stays online, because these events happen rather often. The event on the right was measured during the blackout in Southern Sweden and Eastern Denmark, 23 September 2003 [10]. Such events are very rare and occur only once in 10-20 years. Making DER units tolerate such severe frequency swings could place severe cost constraints. However with a large penetration of DER units their tripping due to severe events will increase the risk of a blackout. There are indications that the Italian blackout of 2003 could have been prevented if distributed generation would have stayed connected to the system.

![Figure 5. Frequency swings measured in the Scandinavian interconnected grid.](image)

The second group of abnormal events of importance to DER units are short-circuits and earth faults. Their main immediate impact on DER units is the voltage dip at their terminals. Two examples of voltage dips due to faults are shown in Figure 6.
Figure 6. Voltage dips due to a fault, with fast protection operation (left) and due to slow protection operation (right). Measurements of phase (left) and line voltages (right).

The event shown on the left in Figure 6 is a moderate dip measured at 10 kV. The cause was a fault in the transmission system correctly cleared by the protection. The duration of the event is less than four cycles and the main dip is in one phase. The one on the right is also measured at 10 kV but the monitor is connected between the phases instead of phase-to-ground. The dip is due to a fault for which the protection takes almost one second to clear. The slow fault clearing makes that the fault develops from a single phase to a three-phase fault. The result is a severe dip: its duration is almost one second and the voltage drop takes place in all three phases. The residual voltage (lowest rms voltage in any of the phases, in percent or pu) is however about the same for both events.

No document exists at the moment that indicates the expected number of voltage dips or frequency swings at a location in the power system. Surveys have been done for some countries, but the published results in most cases only give average values, if any results are published at all. Even when measurement results are available, these have a limited predictive value. Stochastic prediction methods are needed, similar to the methods used to estimate system reliability. Several publications discuss such methods for voltage dips and examples have been shown for both transmission and distribution systems [5][8][9]. No such methods have been applied to predict the number of frequency swings, but their development would be straightforward as the whole system can be modelled as one node for frequency calculations. It will also be easier to obtain appropriate statistics for frequency swings than for voltage dips.

4 Impact of DER on power quality

DER units may have an adverse influence on several power-quality disturbances. The most-discussed issue is the impact on voltage variations. Also increased levels of harmonics and flicker are mentioned as potential adverse impact of DER units. But DER units can also be used to mitigate power-quality variations. This especially holds for power-electronic interfaces that can be used to compensate voltage variations, flicker, unbalance and low-frequency harmonics. The use of power-electronic interfaces will however lead to high-frequency harmonics being injected into the system. These could pose a new power-quality problem in the future.
4.1 Hosting Capacity

To quantify the impact of increasing penetration of DER on the power system, the hosting-capacity approach has been developed. The basis of this approach is a clear understanding of the technical requirements that the customer places on the system (i.e. quality and reliability) and the requirements that the system operator may place on individual customers to guarantee a reliable and secure operation of the system.

The hosting capacity is the maximum DER penetration for which the power system operates satisfactorily. The hosting capacity is determined by comparing a performance index with its limit. The performance index is calculated as a function of the DER penetration level. The hosting capacity is the DER penetration level for which the performance index becomes less than the limit.

A hypothetical example of a hosting-capacity study is shown in Figure 7: the performance index is calculated as a function of the DER penetration level for different investment scenarios. Examples of investment scenarios are placing additional HV/MV transformers or larger cross-section of lines or cables. The result is the hosting capacity as a function of the amount of investment (or any other parameter being varied in the study).

![Figure 7](image)

*Figure 7, performance index for increasing investment (left) and hosting capacity as a function of the investment (right).*

The calculation of the hosting capacity should be repeated for each different phenomenon in power-system operation and design: the hosting capacity for voltage variations is different from the hosting capacity for frequency variations. Even for one phenomenon the hosting capacity is not a fixed value: it will depend on many system parameters like the structure of the network, the type of DER unit (with or without storage; voltage/power control capability, etc), the kind of load and even on climate parameters (for example in case of wind or solar power).

4.2 Low-frequency harmonics

The power-electronic interfaces of DER units contribute to waveform distortion. The current waveform contains frequency components at integer multiples of the power-system frequency and at integer multiples of the switching frequency. We will refer to the former as "low-
frequency harmonics" and to the latter as "high-frequency harmonics".

The level after connection of the DER unit should not exceed the local planning level. The planning level is less than or equal to the voltage characteristic as in EN 50160. The actual choice is made by the network operator and/or the authorities. The concept of hosting capacity can be applied here to obtain the amount of DER units that can be connected to the grid without exceeding the limits. The hosting capacity will depend on the existing disturbance level (sometimes referred to as the "background level").

![Figure 8. Hosting capacity for harmonic distortion.](image)

The concept of hosting capacity is explained for harmonic distortion in Figure 8. The hosting capacity gives the amount of DER that can be integrated into the system without exceeded any performance limit. In this case the limit is the planning level for harmonic distortion. This assumes however that every DER unit has the same distortion (relative to its rated power), which is not the case in practice. When assuming high-distortion interfaces the hosting capacity would be reduced significantly. The current practice is often that a new customer is allowed to connect as long as the distortion level after connection is below the limit. As low-distortion interfaces are more expensive it is likely that the units that are initially connected have a high-distortion interface whereas low-distortion interfaces will only be used when the existing distortion level is high already. The result is a significant reduction in hosting capacity.

A potential problem with increasing levels of DER is the occurrence of resonances due to the increased amount of capacitance connected to the distribution grid. The interface with distributed generation often contains a capacitor. This capacitor may be involved in series or parallel resonances that cause amplification of harmonic distortion produced elsewhere. Manufacturers as well as consultants recommend that capacitor banks be installed with small ac reactors and to be tuned to resonance frequency lower than the lowest harmonics in the actual grid. This problem with occurrence of resonances occurs for induction machines, but not for VSC-based interfaces and for synchronous machines when they provide reactive power themselves so that capacitor banks are unnecessary.

The increased capacitance is however NOT the source of the harmonic distortion. The harmonic currents may be generated by the DER units themselves, by other local equipment,
or by equipment elsewhere. As the current generated by DER units does not contain significant low-frequency harmonics, the source is most likely found in other local equipment or in equipment elsewhere. Despite this, the potential increase of harmonic voltage distortion should be treated as an impact of increasing levels of DER units.

4.3 High-frequency harmonics

Voltage-source converters are known as a source of high-frequency harmonics. The switching frequency and multiples of the switching frequency (1 kHz and up) appear in the spectrum of the current. Pulse-width modulation leads to groups of frequency components around the integer multiples of the switching frequency. Hysteresis control, used in smaller converters, leads to a noise-like frequency spectrum around an "average switching frequency" determined by the design of the converter. If the switching frequency is close to a system resonance it causes a large high-frequency ripple on the voltage. An increasing penetration of DER with power-electronic interfaces, will lead to an increasing level of high-frequency harmonics. The full consequences of this remain unclear. Standardized methods for the measurement and characterisation of high frequency current and voltage harmonics are not yet available.

4.4 Voltage variations

The introduction of DER units will generally lead to an increase of the voltage magnitude experienced by the customers. With highly variable sources of energy (like wind and sun) the voltage magnitude will also show a higher level of changes over a range of time scales. Determining the hosting capacity requires again the choice of a voltage-variation index and an appropriate limit. A possible set of indices and limits is:

- The 100%-interval of the 10-minute rms values should not exceed 90-110% of nominal.
- The 95%-interval of the 3-second rms values should not exceed 90-110% of nominal.
- The 99% value of the Pst should not exceed 1.2.
- The 50% (median) value of the 10-minute very-short variations; shall not exceed 1.0 Volt.

These indices and limits are partly based on international standard documents. To cover changes in voltage magnitude at the time scale between 1 second (flicker) and 10 minutes, the so-called "very-short variation" has been introduced: it quantifies how much individual 3-second values deviate from a 10-minute average voltage [11][12].

The above list of performance indices and limits is certainly not complete. Setting these indices and limits requires a thorough understanding of the requirements placed by the end-customers on the voltage quality. The strength of the hosting-capacity approach is that it relates the limits to be posed on the amount of DER to the limits posed by other customers on voltage quality and reliability.

4.5 Voltage fluctuations

The term "voltage fluctuations" is used to cover a wide range of changes in the voltage magnitude. There is a significant overlap with the term "voltage variations". Here we will however limit the use of the term "voltage fluctuations" to those changes in voltage magnitude that (potentially) lead to light flicker with incandescent lamps, as defined in the
IEC flickermeter standard (IEC 61000-4-15). The severity of voltage fluctuations is quantified through the "short-term flicker severity" (symbol $P_{st}$) and the "long-term flicker severity" (symbol $P_{lt}$). The definition of the short-term flicker severity is such that a level of 1.0 will lead to disturbing levels of flicker being noticed by most observers with standard incandescent lamps.

Fast variations in generated power may lead to voltage fluctuations. These are a concern for those sources for which the available power strongly varies with time: notably wind and solar power. Wind turbines produce a continuously varying output. In [1] three time-scales are distinguished:

- Variations with a frequency of several Hz due to the turbine dynamics, the tower resonance and the gearbox;
- Periodic power pulsations at the frequency at which the blades pass the tower, typically around 1 Hz for a large turbine. These are referred to as 3p-oscillations for three-blade turbines. Detailed measurements presented in [13],[14] show a range of frequencies associated with the rotation of the blades with respect to the tower; from 1p through 18p.
- Slower variations due to changes in wind speed.

It is however pointed out in that the increased emission will at least be partly compensated by the increase in fault level due to the installation of the generators.

There is some evidence that the turbines in a wind park may reach a state of “synchronized operation” thus amplifying the power pulsations due to the tower. The cause of this synchronous operation is not fully clear but it is thought to be due to interactions between the turbines through the network. Synchronous operation can only be expected for sites with a rather constant wind speed not affected by turbulences due to the terrain.

The short-term flicker severity due to individual wind installations, from measurements and simulations presented in different publications, is up to $P_{st}=0.2$ with SCR=20 (SCR is the ratio between the rated power of the wind power installation and the short-circuit power of the grid). In case there are several installations connected close to each other, the flicker level will be higher than with one turbine. But fortunately they will not simply add. According to IEC 61400-21 [15] the $P_{st}$ levels should be added by using the following expression:

$$P_{st} = \sqrt[\scriptstyle N]{\sum_{i=1}^{N} P_{st,i}}$$

(1)

with $P_{st,i}$ the $P_{st}$ contribution from each individual installation. With identical turbines, the contribution from $N$ units is $\sqrt[N]{N}$ times the contribution from one unit. With a contribution of $P_{st}=0.2$ for SCR=20, $P_{st}=0.4$ is reached for SCR=5.
4.6 Faults and voltage dips

An increase in the amount of DER units most likely is associated with a reduction in the number of conventional generation stations being in operation. This replacement will lead to a reduction of the fault level in transmission systems. This makes that voltage dips due to faults are spread over a larger area. Table 1 compares the dip frequency in a transmission system for a high generation scheduling and a low generation scheduling. The low generation scheduling has only half the generation capacity connected to each bus [8].

Table 1, Impact of generation scheduling on dip frequency (number of dips per customer per year) in a transmission system.

<table>
<thead>
<tr>
<th>residual voltage</th>
<th>generation</th>
<th>average</th>
<th>95% site</th>
<th>worst site</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% high</td>
<td>17.9</td>
<td>40.6</td>
<td>44.7</td>
<td></td>
</tr>
<tr>
<td>90% low</td>
<td>25.5</td>
<td>51.6</td>
<td>57.2</td>
<td></td>
</tr>
<tr>
<td>70% high</td>
<td>6.2</td>
<td>15.7</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>70% low</td>
<td>8.4</td>
<td>16.6</td>
<td>18.9</td>
<td></td>
</tr>
</tbody>
</table>

A study of the impact of distributed generation on the voltage-dip frequency is presented in [16]. The increase in dip frequency with increasing amount of DER is shown in Figure 9 for all customers and in Figure 10 for large industrial customers. The dip frequency is calculated for each individual 275 kV and 400 kV substation in a transmission system. In the first case the resulting site indices are weighted based on the maximum active-power consumption of the load connected to this substation. In the second case, the weighting is one for substations supplying a large industrial customer and zero otherwise. The increase in dip frequency is given for dip thresholds of 70%, 75% and 80% of the pre-event voltage. Replacing 60% of the large generator stations results in an increase in dip frequency by 30 to 40%, for the average customer in this specific system. Further studies are needed to assess the impact on individual customers.

Figure 9 Relative increase in dip frequency with increasing percentage of distributed energy resources, for three value of the end-user immunity: 70%; 75% and 80% residual voltage.
5 Sudden loss of DER

The tripping of a single DER unit is primarily a problem for the operator or the owner of the unit. But the loss of many units at the same time reduces the stability, security, and reliability of the network. This problem has received attention recently in countries with a large penetration of wind power, notably Denmark and Germany. But many network operators express the same concern against the large-scale penetration of other distributed energy resources.

A schematic diagram linking a system event with a large-scale blackout is shown in Figure 11. Single-phase faults are more common than three-phase faults but their impact on DER units is less severe. More localized events, like distribution-system faults, may lead to interruptions at distribution level.

![Diagram of system event consequences]

Figure 11, The potential consequences of a fault or loss of generation in a system with a large penetration of DER.

The presence of generation units at distribution level may lead to a reduction in voltage drop when a dip propagates from transmission to low-voltage. For a given location in the network this will result in a reduced dip frequency. For three-phase faults, only synchronous machines
give a significant continuous fault contribution. Induction machines only contribute during the first few cycles of the fault. For non-symmetrical faults also induction machines contribute to the fault, thus reducing the dip frequency. The contribution of power-electronic converters depends on the current-limitation settings, the control algorithm, and the protection used. In general the mitigation effect is larger for non-symmetrical faults than for symmetrical faults.

5.1 Loss-of-generation

The loss of a large generator unit leads to a fast drop in frequency followed by a slower recovery. Examples of these "frequency swings" were shown in Figure 5. Many DER units trip from the grid due to such a frequency swing, at least in part due to enforced sensitive setting of the anti-islanding detection. With low penetration of DER this is merely a concern for the DER operator, but for large penetration it could leave the system with a large shortage of generation. The tripping of DER units as a consequence of the loss of a large generator unit effectively reduces the spinning reserve in the system and thus increases the risk of frequency instability.

A concentration of DER in a part of the system may lead to system overload after a frequency swing. This is already a serious issue in countries with large penetration of wind power, like Denmark and Germany. Even if the tripping of large amounts of wind power is a negligible fraction of the total power in the European interconnected system, locally it may lead to stability problems. In the Danish system, the amount of power generated from wind has already exceeded the load demand a few times (albeit at times of low load). The sudden loss of a large fraction of the wind power will lead to large unexpected changes in the power flow.

At distribution level, the concentration of DER may be even higher than locally at transmission level. Already a moderate growth of DER may soon lead to the amount of DER being several times the local load demand at some medium or low-voltage networks. The sudden loss of DER will probably not lead to overload or stability problems, but may cause unacceptable undervoltages and overvoltages (upon automatic reconnection of the DER units).

5.2 Short circuits and earth faults.

The immediate impact of a short circuit of earth fault is a voltage dip at the terminals of the DER unit. Two examples of voltage dips were shown in Figure 6. From a DER unit viewpoint voltage dips are an even more severe concern than frequency swings. The magnitude of frequency swings is limited, but the same swing appears throughout the entire interconnected system, while voltage dips can locally be of very large magnitude and with a long duration. The tripping is again in part due to the enforced sensitive settings of islanding detection. But as is well known in industrial systems, making equipment immune to voltage dips is not straightforward [5][6].

However the spread of a voltage dip is limited, especially for the long and deep ones. The tripping of DER units due to a voltage dip will only in very rare cases result in frequency instability. The risk of frequency instability increases with decreasing geographical size of the system.
Voltage dips due to faults are however a concern for concentrations of DER, either in certain parts of the transmission system or at distribution level. In the former case the loss of many units due to a voltage dip may lead to stability problems, in the latter case undervoltages and overvoltages are the main concern. The risk of instability and system overload due to the sudden loss of a large amount of DER has resulted in immunity requirements posed by transmission-system operators to DER units. For the time being this is still only an issue for countries with large amounts of wind power and especially where it concerns large wind parks. But similar immunity requirements will likely be introduced with increasing penetration of DER.

For low levels of DER penetration the choice of immunity limits is a matter for the unit operator only. However for larger levels of penetration the tripping of the units may have severe adverse consequences on the system. The reliability of the system is a concern for the network operators, so that they will have to define immunity requirements to keep the unit connected to the system even during a disturbance. The hosting-capacity approach can also be applied to study the impact of increasing levels of DER on local, regional and global reliability, stability and operational risk. Stochastic reliability and security indices are needed to compare with acceptable limits.

Next to these immunity requirements (typically posed by transmission-system operators) several network operators (typically distribution-system operators) place protection requirements on DER units for the maximum tripping time with a given undervoltage. Preventing islanding and the correct operation of the short-circuit protection are typically behind such requirements. Three types of voltage-tolerance curve are plotted together in Figure 12. Most existing connection agreements only pose a protection requirement thus only limiting the immunity of DER units on one side. Future requirements on immunity should be coordinated with protection requirements.

![Figure 12. Voltage-tolerance curves for the immunity requirement (red dashed line); immunity performance (blue solid) and protection requirement (green dotted) for DER grid interfaces.](image)

### 5.3 Responsibility sharing

Moderate dips should be tolerated by equipment as these kinds of events occur between 10 and 100 times per year. Severe ones should be rare in a well-designed and operated system. It is important that agreements between the network operator and the customers (DER...
operators) include information on what kind of dips and an estimated frequency of occurrence that can be expected. Such a responsibility sharing should form the base for immunity requirements on both industrial-process equipment and DER units.

6 Conclusions

The concept of power quality being the sum of voltage quality and current quality can be applied to DER units. Voltage quality is at first a concern for the operator of the DER unit and should be treated in the same way as voltage quality for industrial and commercial customers. Current quality concerns the way in which DER units impact the system and other customers supplied from the same system. The hosting-capacity method allows a quantitative assessment of the impact of DER units. This method can be used to determine which level of DER penetration is acceptable, locally as well as globally. The method has been developed for current quality and voltage quality studies but is also appropriate to study the third aspect of power quality and DER: the tripping of large amounts of DER units due to voltage disturbances in the system.

The main disturbances of concern are frequency swings due to the loss of a large generation unit, and voltage dips due to short circuits and earth faults. A large overall penetration of DER may lead to frequency instability, especially after the loss of a large generation unit. Local and regional concentrations of DER may lead to stability and security problems at transmission level and under and overvoltages at distribution level.

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References


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Figure 24. Voltage-tolerance curves for the immunity requirement (red dashed line); immunity performance (blue solid) and protection requirement (green dotted) for DER grid interfaces.
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Table 2, Impact of generation scheduling on dip frequency (number of dips per customer per year) in a transmission system.