Integration of Distributed Generation in the Power System – A Power Quality Approach

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***Abstract*—This paper gives an overview of the design and operation issues in distribution and transmission systems due to the integration of distributed generation. The hosting-capacity approach has been developed to obtain a quantitative measure on the amount of generation that can be connected without impairing the performance of the system. The hosting-capacity approach requires a set of well-defined performance indices together with acceptable limits.**

***Index Terms*—Distributed generation, power quality, power-system reliability, voltage control, operational security.**

I. Introduction

THE integration of new production sources in the grid is one of the most important challenges for power transmission and distribution systems in many industrialized countries. Distribution systems are designed for radial operation and the presence of generation units at distribution level was not considered in the design. This in itself does not mean that distributed generation (DG) will cause problems but it does lead to a serious fear among many distribution-network operators that the reliability and quality of the supply can no longer be guaranteed. Several potential problems have been reported in literature, with voltage control being widely considered the most serious one [2][3].

The introduction of minor amounts of DG will likely result in a reduced loading of the transmission system. However the often-unpredictable variations in produced power and the closure of large power stations may adversely impact the transmission system as well.

Opinions on the amount of DG that can be safely connected to the power grid range from "almost nothing" to "almost everything". The former opinion is often based on worst-case scenarios and reported problems. The latter opinion is often based on the control possibilities of DG together with developments in (power) electronics and communication, seen as almost limitless.

This paper will start with a discussion of the different ways in which DG interacts with the power grid. The interaction between the grid and its customers, as is the basis for most of the work on power-quality, is used as a starting point. The approach proposed in this paper is to define a number of performance indicators for the power supply together with appropriate limits. The use of performance indicators is common within power quality and reliability, where they are commonly referred to as "power-quality indices" or "reliability indices". This approach can be extended to other aspects of power system design and operation.

This paper will next continue with a discussion on the impact of DG on distribution systems and on transmission systems. The paper closes with a short discussion on the control possibilities of DG and an overview of the positive and negative impacts of DG on the reliability as experienced by the end-customer.

II. Power Quality and Distributed Generation

A. A Modern View on Power Systems

Power quality concerns the interaction between the power network and its customers [1][2][3]. Power quality consists of two parts, corresponding to the direction of the impact. *Voltage quality* concerns the way in which the network impacts the customer and customer equipment. *Current quality* concerns the way in which the customer impacts the network.

Power quality is one of the aspects of the modern view on power systems, as shown in Fig. 1. The open electricity market and the integration of new sources of energy in the grid are two other aspects of this view.

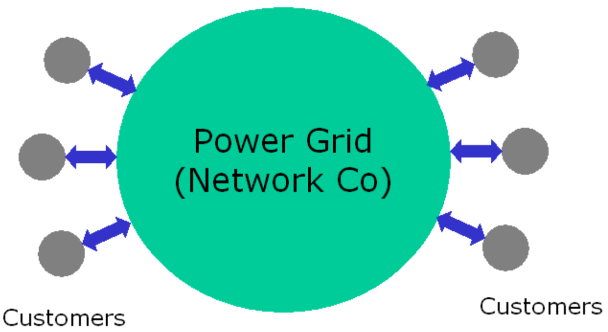

Fig. 1. Modern view of the power system.

Most of the work on power quality has been directed

Keynote paper presented at the 13th International Conference on Harmonics and Quality of Power, Wollongong, Australia, 28 September – 1 October 2008.

This paper is based in part on the work done within the EU-DEEP project (funded by the European Commission, Svenska Kraftnät and the Swedish Energy Administration) and within the VindForsk program.

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978-1-4244-1770-4/08/$25.00 ©2008 IEEE

towards consumers of electricity, especially towards industrial installations. Under the modern view on power systems, as visualized in Fig. 1, producers and consumers of electricity are both customers. Power quality will thus also concern the interaction between the power grid and DG. The same distinction between voltage quality and current quality can be made, as in Fig. 2 and Fig. 3.

B. *Voltage Quality*

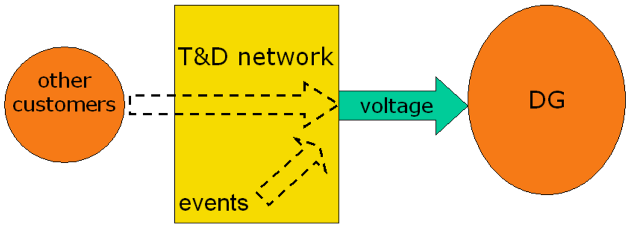

Fig. 2. Voltage quality: impact of the grid on distributed generation. The quality of the grid voltage in its turn is caused by other customers and by events in the network.

Distributed generation units are affected by the voltage quality in the same way as all other equipment (Fig. 2). The impact of voltage disturbances includes a reduction of the lifetime of equipment, erroneous tripping of the equipment and damage to equipment. An important difference between DG and other equipment connected to the grid is that the erroneous tripping of generator units may pose a safety risk: the energy flow is interrupted potentially leading to machine over-speed and large over-voltages with electronic equipment. The choice of immunity level of generators against voltage disturbances is the same as for other equipment. The generator units should be immune against all variations during normal operation and against all events that occur regularly. The immunity of the generator units against not so common events like voltage dips is a matter of local economic optimization where the costs of improved immunity is traded against the losses due to tripping of the generator unit. A description of the voltage quality that can be expected at the terminals of a generator unit connected to the distribution network can be found in a number of international standard documents or be obtained from local measurements.

C. *Current Quality*

The generator current may impact the voltage quality and reliability experienced by other customers (Fig. 3). Some of the adverse impacts of DG are the cause for serious concern among network operators. The impact of DG on the voltage quality and reliability experienced by other customers will be discussed in detail in the forthcoming sections of this paper.

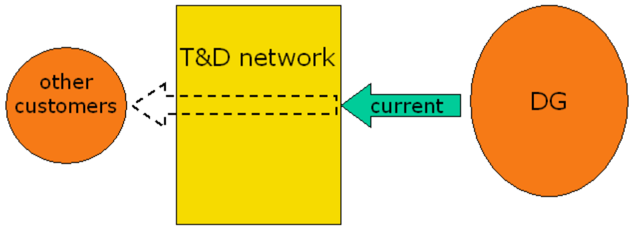

Fig. 3. Current quality: impact of distributed generation on the voltage quality experienced by other customers.

D. *Unit Tripping*

A third aspect of power quality is the impact of equipment tripping on the voltage quality experienced by other customers. A voltage-quality event (e.g. a voltage dip or a large drop in frequency) results in the loss of a large customer or a large group of customers. This could impact the power flow in such a severe way that it results in a major system collapse. This has not been a widespread concern for consuming customers but has recently become a serious concern with generating customers.

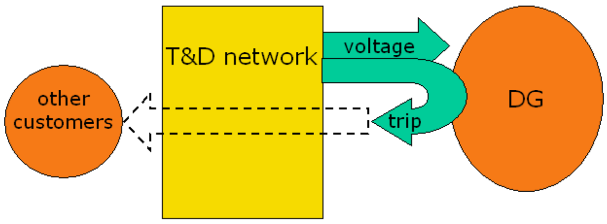

Fig. 4. Voltage quality events causing tripping of distributed generation impacting other customers.

As shown schematically in Fig. 4 a voltage-quality event could result in the loss of DG units. This in turn could result in further reliability and voltage quality disturbances for other customers. Some examples will be discussed in the forthcoming sections.

III. The Hosting-Capacity Approach

To allow for an open discussion on the amount of distributed generation that can be integrated in the power grid, the so-called ``hosting-capacity approach'' has been developed as part of the EU-DEEP integrated project [4][5]. The foundation of the approach is a quantification of the tasks of the network operator.

A. *Tasks of the Network Operator*

In most countries the tasks of the network operator are defined in national legislation. In Europe a number of European directives are in place to harmonize the national legislation on this. The exact terminology varies between countries but corresponds in most cases to the following three tasks:

- Enable the transport and distribution of electrical energy between generators and consumers.

- Ensure high reliability and voltage quality.
- Allow the integration of renewable energy sources in the grid.

It is not always clear which of the three tasks is most important, but the general interpretation is that the integration of renewable energy sources should not interfere with the other two tasks. To assess if and when the integration of DG interferes with the other two tasks, measurable definitions of transport capacity, reliability and quality are needed. These “performance indicators” or “performance indices” play an important role in the hosting-capacity approach.

B. The Hosting-Capacity Approach

Once the performance indicators are in place, the hosting capacity approach becomes straightforward; it is shown schematically in Fig. 5.

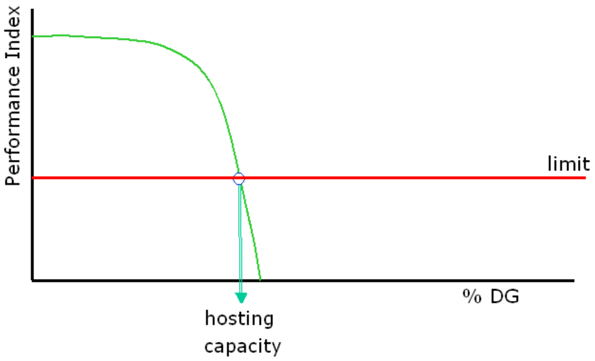

Fig. 5. Basic principle of the hosting-capacity approach.

For any performance index, an acceptable limit is chosen. The value of the performance index is next calculated as a function of the amount of DG integrated in the grid. The hosting capacity is the highest amount of distributed generation that can be integrated without the performance limit being violated.

In Fig. 5 the value of the performance index is assumed to be 100% in the ideal case and to reduce with increasing amount of DG. The hosting capacity is the amount of DG that makes the value of the performance index drop below the limit. In power quality studies it is more common to have zero as the ideal value (think of THD as an example). Increasing amounts of DG will impact the value of this index and the hosting capacity is where the limit value is exceeded.

There are also cases where small amounts of distributed generation improve the performance (losses, undervoltages and reliability are possible examples), but larger amounts result in a deterioration of the performance.

C. Application and Challenges

The application of the hosting-capacity approach requires the following steps to be taken:

- Choose a phenomenon and a performance index.
- Determine a suitable limit for the performance index.
- Calculate the value of the performance index as a function of the amount of distributed generation.
- Obtain the hosting capacity.

The main challenges in the approach are the choice of appropriate and widely-accepted performance indices and limits. A significant amount of work has been conducted on this where it concerns power-quality variations like harmonics, voltage variations, unbalance and flicker. But further work is needed to cover the whole range of transport capacity, reliability and power quality. The discussion on the integration of DG in the grid cannot be seen independent from the discussion on reliability and power-quality objectives.

IV. Distribution Systems

The impact of distributed generation on distribution system has been discussed a lot in the literature. Many publications however discuss worst cases or extreme cases, typically the connection of a generation unit to a remote part of the distribution system. Of more interest, and in line with the approach propagated by the authors, is to find limits to what is acceptable.

A. Voltage Variations

A general rule in the design of distribution feeders is that the voltage magnitude becomes lower when moving along the feeder. Integrating generation units at distribution level makes that this condition may no longer be true and overvoltages may occur. Small amounts of DG do however have the ability to mitigate undervoltages. Only for larger amounts will the overvoltage become a concern.

Calculating the hosting capacity requires detailed stochastic models of load and generation together with the feeder impedances. It also requires appropriate performance indices and limits. Within Europe the voltage-characteristics standard, EN 50160, states that the 10-minute rms voltage shall be between 90% and 110% of the nominal voltage most of the time and between 85% and 110% all of the time. Discussions are ongoing about more strict limits. These limits are requirements on the network operator. When it comes to connecting new customers, like DG, the so-called “planning levels” are more commonly used. Planning levels are stricter than voltage characteristics to allow for a margin to cover future growth or other uncertainties.

When using the 10-minute values and 110% of nominal voltage, a higher hosting capacity will be obtained than when using, for example, 3-second values and 106% of nominal voltage.

Consider as an example a generator unit connected to a remote 10-kV feeder. The total load is assumed to be uniformly distributed along the medium-voltage feeder. The local low-voltage load is supplied through a distribution transformer with turns ratio 9.5kV/400V. Allowing a voltage equal to 1.10 pu on a 400-V base at the secondary side of the distribution transformer results in the following approximated expression for the power production.

$$P_{\text{gen}} < \frac{1.046 - U_{\text{MV}}}{R} + \frac{P}{2} + \frac{X}{R} \times \frac{Q}{2} \qquad (1)$$

where P and Q are the feeder load and $R+jX$ the feeder impedance; U_{MV} is the voltage at the start of the feeder, in per unit on a 10-kV base. For a deterministic study the minimum load and the upper limit of the deadband of the tap-changer should be taken and the hosting capacity is obtained by changing the inequality (<) in (1) to equality (=). For a stochastic study, the probability that the inequality is false shall not exceed a predefined small value.

B. Harmonic distortion

When studying the impact of distributed generation on the harmonic distortion, three different aspects should be considered.

- The generation unit may inject harmonic currents resulting in an increase in voltage distortion. This effect is small and is unlikely to be of importance. Synchronous and induction machine interfaces may even give a reduction in some lower-order harmonics. Power-electronic interfaces will inject some harmonics but the waveform is in general closer to a sinewave than for many loads.
- The capacitances at the interface of some small generation units will result in a shift in resonance frequencies and in the creation of new harmonic resonances. Resonances in the range between 1 and 2 kHz were measured in a residential area with large amounts of solar panels [6]. Theoretical considerations showed that resonance frequencies below 1 kHz are unlikely due to small generation units [7]. When resonance frequencies are already close to one of the lower-order harmonics, the additional capacitance may move the resonance even closer.
- In the frequency range above 1 or 2 kHz, small generation units with power-electronics interface will be a major source of distortion. A general study has indicated that already a very small number of units may result in reasonable limits being exceeded [8][9].

C. Protection

The presence of DG with induction machine or synchronous machine interface will result in additional contributions to the fault currents. These contributions are most severe with synchronous-machine interface and may result in both unwanted trip and fail-to-trip of the overcurrent protection in distribution systems. Different hosting capacities should be distinguished.

1. <u>Changing protection settings</u>. This may be required already for small levels of DG integration and requires only a change in the current limits.
2. <u>Additional time step in protection coordination</u>. When a feeder contains a high amount of DG, more than about 25 to 50% of the transformer rating according to preliminary studies [10][11], coordination problems occur that require the introduction of a new time step. This is in itself easy and cheap but it could cause problems with the fault-current withstand of transformers or cables as well as with personnel safety. If such problems occur, investments are needed where a dedicated transformer to the DG unit is a possible solution.
3. <u>Additional circuit breaker</u>. For a long feeder the difference between the highest load current and the lowest fault current may become too small for a reliable protection. This requires the installation of a circuit breaker somewhere along the feeder. For long feeders that are close to their maximum length, the installation of a small amount of DG may already require this.
4. <u>New protection concepts</u>. When two or more feeders from the same transformer have a significant amount of DG, it is no longer possible to obtain selectivity with only overcurrent protection. Other solutions are needed like directional protection and/or communication between relays.

D. Impact of a Fault

It was mentioned before that the immunity of generator units against voltage-quality events like dips is a matter of local optimization by the owner or operator of the unit. Next to that the distribution network operator may put requirements on the maximum time the unit may remain connected during a voltage reduction at its terminals. This forced tripping is aimed at preventing interference with the overcurrent protection and at protecting the grid against uncontrolled islanding.

The consequence of all this is however that a fault somewhere in the distribution or transmission grid will result in tripping of a large fraction of the generation units connected to a distribution feeder. The consequence of this for the voltage magnitudes along the feeder is shown in Fig. 6. It is assumed that the units are automatically reconnected after a few minutes.

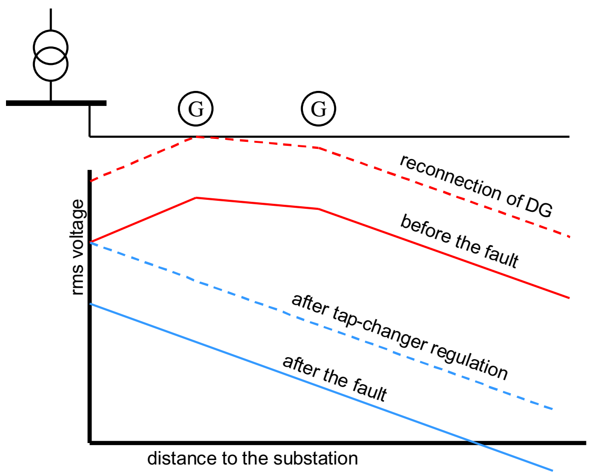

Fig. 6. Impact on the voltage profile along a feeder of a fault followed by tripping and reconnection of the distributed generation.

Under the existing regulations in most countries, where only 10-minute average voltage magnitudes are considered, the resulting voltages do not violate any regulation. They may however still result in equipment damage or production stoppages beyond what the initial voltage dip would have resulted in.

E. Component Overload

The introduction of DG will impact the power flow in the distribution network. This will impact the distribution system losses and may result in overload of distribution feeders. For large amounts of DG also the losses and the loading situation in the transmission system will be impacted.

As DG is connected closer to the load than most conventional generation, the power has to be transported less far, so that the losses become less and the loading situation improves.

The most advantageous situation occurs when the DG installation is at the same premises as the load. Combined-heat-and-power has in this respect a great advantage over for example wind power.

Small amounts of DG will always result in an improvement of the loading situation and a reduction of the losses. For larger amounts of DG overloading may occur and the losses may increase.

Consider a location along a long distribution feeder, with total downstream load equal to $L(t)$ and total downstream generation $G(t)$. We may assume that no overloading situation exists before the introduction of DG. As long as the maximum power flow after connection is less than before, there will be no overload.

This condition is fulfilled when:

$$G_{\max} < L_{\max} + L_{\min} \qquad (2)$$

As long as the maximum generation is less than the sum of minimum and maximum load, for every location of the feeder, no overloading will occur. When the maximum generation exceeds this first hosting-capacity level, additional studies are needed to determine a second hosting-capacity level. These additional studies should include the correlation between variations in load and variations in generation and the actual loading margins at the different locations along the feeder.

For a more detailed assessment the reactive power should also be included. The approach is similar but the calculations become more complicated. A case where the difference in first hosting-capacity level could be significant is when the interface consists of induction machines. Their reactive-power consumption could cause overloads faster than would be found from the above approach.

From the above reasoning it is concluded that overloading problems are expected first in parts of the network that are lightly loaded: remote rural areas. The connection of a generator with a large capacity compared to the load downstream of the connection point, could result in overloading of the distribution feeder upstream of the connection point. This is often the case with wind-power installations in remote rural areas.

F. Transport Losses

Estimating the increase or decrease in losses due to the introduction of DG requires much more detailed studies than estimating if a possible overload may occur. An increase in losses can be compensated by a reduction at another moment in time or at another location. What matters are the total losses over all feeder sections and integrated over time.

As long as $2L_s(t) - G_s(t) > 0$, for all t and all feeder sections s, the total losses are certainly reduces. However this is an overly strict condition, far below the actual hosting capacity (where losses would start to increase).

Assuming that load and generation have similar behavior in time for all feeder sections the following condition can be obtained:

$$G_{mean} < 2 \times L_{mean} \qquad (3)$$

In words: as long as the average generation is less than twice the average load, no increase in losses is expected. The condition that load and generation have the same time behavior may seem rather unrealistic. However the result will be valid approximately as long as the generation pattern is not in opposite with the load pattern.

It should also be noted that an exact calculation of the hosting capacity is not needed where the losses are concerned. An increase in losses by some tens of percent (compared to the existing level of losses) is not really a concern, neither from a cost viewpoint (losses are a minor part of the total cost of electricity supply) nor from an environmental viewpoint (the gain by using renewable or energy-efficient sources is much higher than the increase in losses).

A more detailed study of the losses may however be needed to determine the economic impact on the network operator or the specific reduction in losses due to one DG unit. Such a study would require detailed information on load and generation patterns and their correlation.

V. Transmission Systems

The impact of DG on the transmission system is initially small. From a transmission-system viewpoint the additional generation will result in a reduction of the load, which in turn results in a stronger and more reliable transmission grid.

With further increase in DG, the conventional units with the highest marginal costs will be taken out of operation during periods with low load and/or high amounts of power produced by distributed-generation units. This will result in a weaker grid.

A. Harmonics and Flicker

The distributed-generation units will most likely only produce active power at fundamental frequency. Fast fluctuations in active and reactive power and most of the harmonic currents will still need to be produced by the shrinking amount of conventional units. The result may be an increase in the flicker level and harmonic voltage distortion at transmission level. The actual increase depends strongly on the specific local situation. The closure of just one conventional generator may be sufficient to cause distortion or flicker levels above the planning levels.

It should be noted that also the open electricity market, without DG, might result in large conventional units being taken out of operation, even if these units are essential for maintaining acceptable distortion and flicker levels.

B. Voltage Dips

The impact of distributed generation on the voltage-dip frequency is similar as its impact on distortion and flicker level. As less large power stations are in operation, a fault in the transmission grid will cause a dip over a larger area. From the viewpoint of an individual customer the number of voltage dips due to transmission-system faults will increase. The impact has been quantified for a large transmission system in its current state and with 20% wind power [12]. The results are shown in Fig. 7. The "0%-wind" case assumes that the load is equal to the peak load during 50% of the year and half of the peak load during the remaining 50% of the year. The "20%-wind" case assumes that the amount of energy produced by wind equals 20% of the peak load and is constant during the year. The dip frequency is in arbitrary numbers; it is the comparison that matters. Each dot in the figure corresponds to one transmission substation.

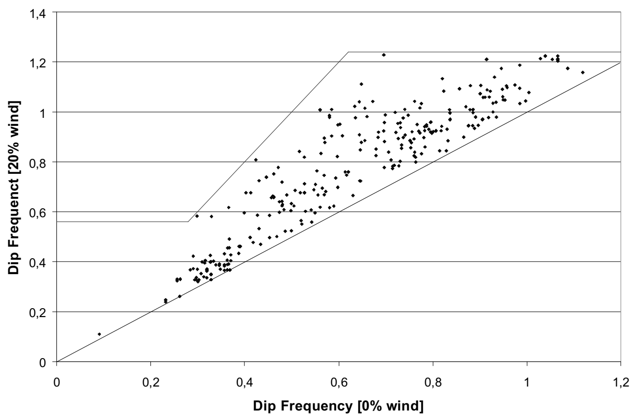

Fig. 7. Impact of 20% wind power on the voltage-dip frequency.

The diagonal line corresponds to no change in dip frequency. The upper curve is a somewhat arbitrary performance criterion. The conclusion from this study is that even 20% wind (average production as a percentage of the peak load) will not result in unacceptable increase in voltage-dip frequency.

C. Impact of a Fault

The impact of a fault at the transmission level is at first very similar to the impact of a fault at distribution level. The fault may cause the tripping of a large part of the small generation units exposed to the resulting voltage dip. There are however a number of essential differences:

- A fault at transmission level will result in a dip over a large area so that the loss of generation will likely be much larger than for a fault at distribution level.
- A fault at transmission level and the subsequent removal of the faulted component by the protection will result in a weakening of the transmission system.
- Interruptions and voltage-quality violations at distribution level are unwanted but acceptable up to a certain frequency. Interruptions at transmission level (often referred to as "black-outs") are unacceptable.

The loss of a large amount of generation due to a fault at transmission level will result in a sudden increase of transmission-system loading at the same time that the system is weakened due to the loss of the faulted component.

D. Operational Security

The operational security of the transmission grid is guaranteed by the so-called "(N-1)-criterion". This criterion states that the operation of the transmission system shall be such that the loss of any single component does not result in loss-of-load. The large conventional power stations play an important role in maintaining the stability of the transmission system. The dispatch of these large power stations is therefore an important tool for the system operator (TSO or ISO) in fulfilling the (N-1)-criterion. When the electricity market results in insufficient large power stations being in operation, the system operator will intervene in the market. This however assumes that there are large power stations available. With increasing amounts of power generated by non-dispatchable distributed generation with low marginal costs, it will no longer be economically attractive to maintain large power stations with high marginal costs or to build new ones. Situations may arise in which the (N-1)-criterion cannot be fulfilled anymore.

Another important impact of DG on the transmission-system security is related to the uncertainty of the produced power. The power produced by weather-related sources like wind and solar power is not only strongly fluctuating but is also difficult to predict accurately. This requires additional operational margins beyond the (N-1)-criterion.

VI. Using the Control Possibilities of Distributed Generation

In most of the preceding parts of this paper it has been assumed that the distributed generation does not contribute actively to the operation of the distribution or transmission system. The presence of generation close to the load does however offer many opportunities to actually improve reliability and voltage quality.

At distribution level the obvious application is to use the generation units as part of the voltage control of long rural feeders. This requires a power-electronics or synchronous-machine interface and coordination with other types of voltage control along the feeder.

With industrial installations the flicker and harmonics-mitigation capabilities of power-electronics interfaces can be used to improve the quality of supply. This requires the use of suitable control algorithms, many of which have been proposed in literature already.

At transmission level, DG could become a resource for the system operator. Together with voluntary load reduction, the DG could be treated as a “virtual dispatchable generator”. This requires the setting of clear rules and a well-functioning ancillary services market as well as communication between the control room and the small generator units.

VII. Reliability of Supply

The introduction of DG will result in an improvement of the supply reliability in a number of ways.

- As DG is often closer to the loads it will reduce the loading of both transmission and distribution systems. A reduction in loading at distribution level reduces the risk of an interruption due to overloading of a component. At transmission level the risk of a large-scale blackout is reduced, as the introduction of DG will effectively result in a reduction of power flows through the transmission system.
- The introduction of DG will also result in more generation margin and this reduces the risk of a shortage of generation.
- DG can help in allowing a faster restoration of the supply after a fault on a distribution feeder. When supplying load from a back-up feeder overloading during peak load is a major concern. However DG will reduce the peak load and thus the risk of overloading.
- In the future DG could be a resource during rebuilding of the network after a massive blackout.
- DG even offers the possibility of controlled island operation during an interruption. This however requires significant investments in both the DG units and the distribution network. Controlled island operation of individual customers is easier but even here a number of challenges remain.

There are however a number of new threats to the system reliability due to the introduction of DG. They may not all be serious threats but it is worth further studying them to quantify the impact.

- The problems with protection coordination were mentioned earlier in this paper. The introduction of DG in all cases changes the fault currents and this will increase the risk of an incorrect protection operation. From the viewpoint of the end-user incorrect protection operation results in a higher expected number of interruptions. Interruptions associated with protection mal-operation are also often longer than normal interruption as it will be more difficult to find the cause of the fault. Note that it will rarely be immediately obvious that the protection operated incorrectly.
- When connecting large DG units to remote locations in rural networks, overloading could occur increasing the risk of an interruption.
- A potential risk with the connection of DG units is that they may be installed and maintained by independent companies that do not follow the quality routines that are common for distribution companies. This could result in a rather high failure rate of the DG units with the risk of this spreading to the distribution network.
- The often unpredictable behavior of DG units during a transmission-system disturbance could increase the risk of a large-scale blackout.
- In the long term the installation of DG could result in the closure of conventional power station or in less than sufficient growth in the number of conventional stations. As DG units are typically non-dispatchable this could result in a shortage of generation or in insufficient operational security. Both require rotating interruptions and increase the probability of a large-scale blackout.

VIII. Conclusions

The hosting-capacity approach is a systematic way of determining how much distributed generation can be connected to a power system without resulting in unacceptable reliability or voltage quality for other customers. An important part of the approach is the definition of performance indicators with appropriate limits. The experience on such indicators (“power-quality indices” or “reliability indices”) within the power-quality field can be used as an important starting point for the further development.

The impact of distributed generation on distribution and transmission systems goes far beyond power quality. However the power-quality approach propagated in this paper, based on performance indicators and limits, can be applied to any aspect of power system design and operation.

IX. Acknowledgment

Thanks to André Even for suggesting the use of a hosting capacity and to many others within the EU-DEEP consortium for the discussions contributing to the knowledge presented in this paper.

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XI. BIOGRAPHIES

Math Bollen (M'93–SM'96–F'05) received the M.Sc. and Ph.D. degrees from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1985 and 1989, respectively. Currently, he is manager power quality and EMC at STRI AB, Ludvika, Sweden and guest professor at Luleå University of Technology, Skellefteå, Sweden. Before joining STRI in 2003, he was research associate at Eindhoven University of Technology, lecturer at the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., and professor in electric power systems at Chalmers University of Technology, Gothenburg, Sweden. His current research interests include power quality, reliability, and integration of distributed generation and wind power in the grid. He has published more than 100 papers including a number of fundamental papers on voltage dip analysis and two textbooks on power quality, "*understanding power quality problems*" and "*signal processing of power quality disturbances*".

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Fainan Hassan (M'96) received the PhD degree in electrical engineering from the Energy and Environment Department, Chalmers University of Technology, Gothenburg, Sweden, in 2007. Currently she is a senior engineer at STRI AB, Ludvika, Sweden. She has a six years experience as a teacher assistant for undergraduate and graduate courses in power system and power electronics from Mansoura University, Egypt. Her research interests include the control of power electronics, power electronics applications in power systems, power quality, distributed generation, and the utilization of renewable resources. She has published seven papers, of which one of them in the Wind Energy Journal and six are published in well-known IEEE international conferences, regarding integration aspects of converter interfaced distributed generation in the distribution grid. She has been awarded a high quality paper certificate from the IEEE Power Tech conference that has been held in St. Petersburg, in June 2005