Electrical Power Quality & Utilization Magazine
Volume 3, Issue 2

Leonardo ENERGY

# Overvoltages due to Wind Power - Hosting Capacity, Deterministic and Statistical approaches

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Available online October 2008

EPQU Magazine

This paper introduces methods to quantify the impact of wind power and other types of distributed generation on the overvoltage risk. The so-called hosting capacity approach, introduced in the very first issue of this magazine, is used as the basic approach. Both a deterministic and a statistical approach are introduced. The deterministic approach is suitable for generation with a constant production most of the time. However, it is shown that a deterministic approach could easily result in an unnecessary barrier against the introduction of wind power. For any method used to determine the hosting capacity, a serious discussion is needed about overvoltage indices and objectives.

## Introduction

Most European countries, as well as countries outside of Europe, have set targets for the amount of wind power or other renewable sources that should be integrated in the power system 10 to 20 years from now. The ability of the power system to absorb this amount of new sources of energy is rarely addressed when setting the targets.

The advantages of renewable sources of energy are obvious and beyond discussion in this paper. However, these advantages do not remove the risk of interference between these new sources and the quality and reliability as experienced by the existing customers of the network [1][2][3]. The hosting capacity approach has been introduced in the very first issue of this magazine [4], as a method for quantifying this challenge. The hosting capacity is a systematic method that gives the amount of new sources that can be connected without the need for major investments. This paper will address the hosting capacity, as it would result from the setting of overvoltage limits.

## Hosting-Capacity Approach

The basis of the hosting-capacity 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 high-quality operation of the system.

The hosting capacity is determined by comparing a performance index, calculated as a function of the amount of distributed generation, with the limit of satisfactory operation of the power system. The hosting capacity is the maximum amount of distributed generation at which the performance index does not violate the limit. It may also be calculated as a function of the amount of investment, the result being the hosting capacity as a function of the amount of investment (or any other parameter being varied in the study). Examples of investment scenarios would be the placing additional HV/MV transformers or the provision of lines or cables of larger cross-section.

For many phenomena (``power-quality disturbances'') the index value is zero in the ideal case (e.g. the total harmonic distortion or THD for waveform distortion). The index value versus amount of generation will be as shown in Figure 1 and the hosting capacity will be the amount of generation for which the index exceeds the limit.

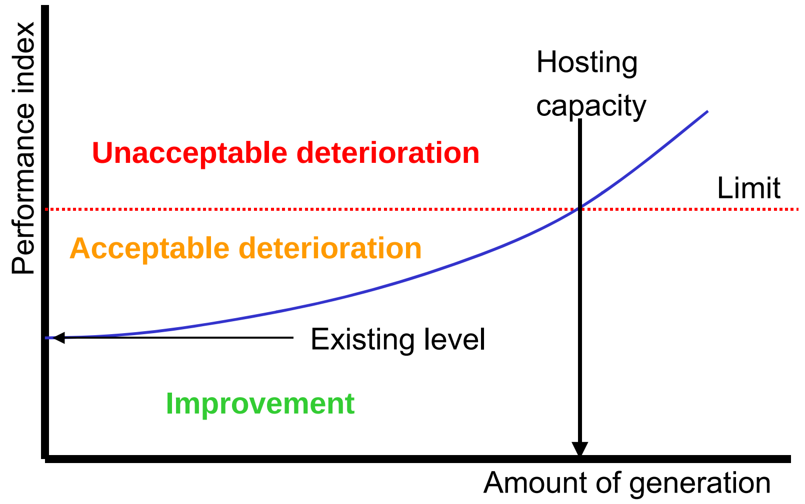



*Figure 1. Hosting-capacity concept for power-quality variations.*

The calculation of the hosting capacity should be repeated for each different phenomenon in power-system operation and design since, for instance, the hosting capacity for voltage variations will be different from that for frequency variations. Even for one phenomenon the value of hosting capacity will depend on many system parameters, such as the structure of the network, the type of generation 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), etc.

## Hosting Capacity and Overvoltages

The presence of generator units in medium-voltage and low-voltage networks results in an increase in the voltage magnitude for the end-users. The origin of this problem is discussed in detail in the literature: the main concern is the voltage rise in those low-voltage networks for which the maximum voltage magnitude is already rather high during periods of low load. Those networks typically show a large range between maximum and minimum voltage magnitude.

If a generator injects a constant amount of power all of the time, both the maximum and minimum voltage will rise. For small amounts of distributed generation this will mitigate undervoltages and as such improve the quality of supply. However larger amounts of distributed generation will result in overvoltages.

For fluctuating sources of energy, like sun and wind, the rise in minimum voltage is small or negligible so the result is a rise in maximum voltage without the associated rise in minimum voltage. This is the most severe situation from a network design viewpoint.

As the voltage rise is proportional to the amount of active power injected, the difference between the highest voltage magnitude, before connection of distributed generation, and the upper voltage limit is an important factor for determining the hosting capacity.

This is illustrated in Figure 2, where the "voltage margin" is shown for measured voltages. The figure shows the 1-second voltages recorded in each of the three phases during a 2.5-day period. The maximum voltage magnitude is 239.3 V; the overvoltage limit is set at 248.4 V (108% of the nominal voltage); the resulting voltage margin, available for the connection of distributed generation is 9.1 Volt, or 3.9% of the nominal voltage.

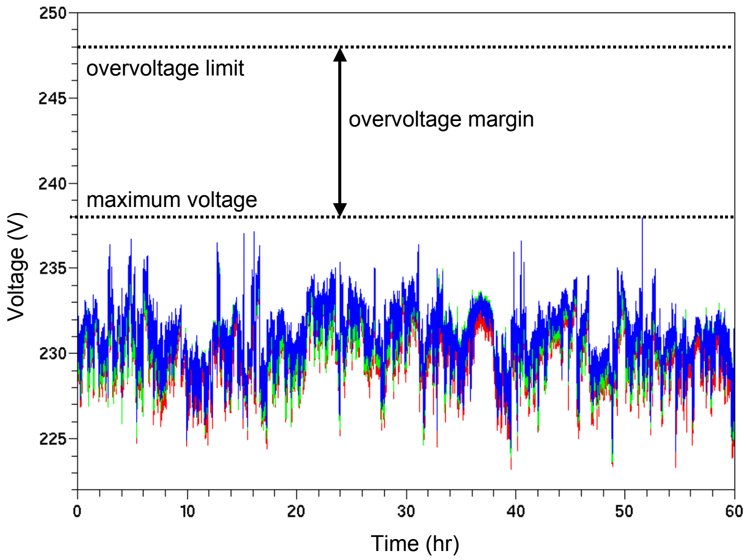



*Figure 2. Overvoltage margin as the difference between the overvoltage limit and the maximum voltage. The red, green and blue curves indicate the measured 1-second rms values of the three phase-to-neutral voltages during a 60-hour period.*

The overvoltage margin $\Delta_{max}$ is available for voltage rise due to distributed generation. The voltage rise due to a power injection $P_{gen}$ connected at a voltage level $U$ is equal to:

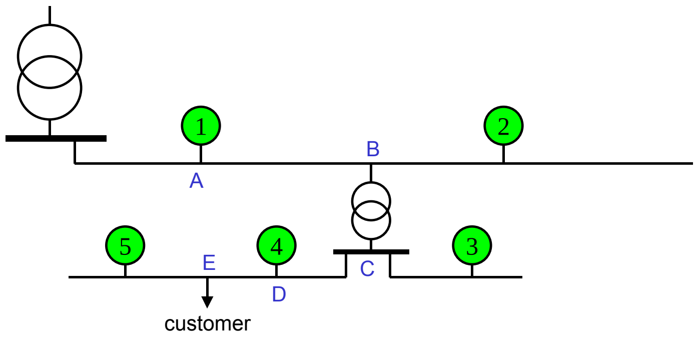
$$\frac{\Delta U}{U} = \frac{R \times P_{gen}}{U^2} \qquad (1)$$

where $R$ is the resistive part of the source impedance (without the DG contribution) at the point-of-connection between the generator and the customer exposed to overvoltages. Some examples of the location of the point-of-connection (PCC) for a customer at low voltage are shown in Figure 3.

The maximum amount of power that can be injected without reaching the overvoltage limit (i.e. the "*hosting capacity*") is obtained from:

$$P_{\max} = \frac{U^2}{R} \times \delta_{\max} \qquad (2)$$

with $\delta_{max}=\Delta_{max}/U$ the ratio between the voltage margin and the nominal voltage. In deriving (2) is has been assumed that the generator does not produce or consume any reactive power. The ratio $\delta_{max}$ is independent of the voltage level. In the example from Figure 2 this ratio would be equal to 0.039, independent of the voltage level at which the generator would be connected. For a point-of-common coupling at 6 kV the permissible rise in voltage magnitude is 3.9% of 6 kV; for a point-of-common coupling at 22 kV, the permissible rise is 3.9% of 22 kV.




| DG | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| PCC | A | B | C | D | E |

*Figure 3. Point of common coupling for different locations of distributed generation with a customer at low voltage.*

In most networks the HV/MV transformer is equipped with an automatic tap changer, keeping the voltage at the mean MV bus constant. For time scales larger than a few minutes (the response time of the tap changer) the resistance *R* in the above expressions should be measured between the mean MV bus and the point-of-common coupling. For shorter time scales (like 1 second) the resistive part of the total source impedance at the point-of-common coupling should be used. However, the main power variations occur at time scales longer than one minute, even for wind and solar power. Next to that the MV and LV networks typically dominate the resistive part of the source impedance.

Consider, as an example, a 20-km rural 33-kV feeder, 35 $mm^2$ Aluminium, 840 mΩ/km. Using (2) gives a hosting capacity equal to 2.5 MW. For a 400-Volt connection point with a source resistance of 20 mΩ, the hosting capacity is 300 kW. In both cases the voltage margin equal to 3.9% of nominal voltage has been used.

It is important to emphasize that the hosting capacity as obtained from this method is strongly dependent on the index used to quantify the overvoltages and on the overvoltage limit used. The overvoltage margin $\Delta_{max}$ has been calculated for the same location as in Figure 2, using three different overvoltage limits (108%, 110% and 112% of nominal voltage) and using three different indices for quantifying the overvoltage: the 1-second, 1-minute and 10-minute rms voltages. The results are shown in Table 1. Both the time-aggregation window and the overvoltage limit have a significant impact on the overvoltage margin and thus on the amount of distributed generation that can be connected.

*Table 1. Overvoltage margin at the same location for different values of the window used to calculate the rms voltage and for different overvoltage limits.*

| | 108% | 110% | 112% |
|---|---|---|---|
| 1-sec | 9.1 V | 13.7 V | 18.3 V |
| 1-min | 11.8 V | 16.4 V | - |
| 10-min | 13.8 V | - | - |

# Statistical Approach

## Calculation Method

To estimate the probability that the voltage magnitude will exceed a certain level, measurements of voltage magnitude and of wind-power production have been used. The measurements were obtained at several locations around the world, although about half of the measurements are from locations in Sweden. All measurements were performed close to the end-user equipment in low-voltage networks with a nominal voltage around 230 Volt.

From a measurement time series of wind power production (more than 3 years of hourly averages) a time series of the voltage rise was obtained:

$$\Delta U(k) = \Delta U_{\max} \times \frac{P(k)}{P_{\max}} \qquad (3)$$

where $P(k)$ is the time series of the wind-power production, $P_{max}$ the maximum wind-power production as obtained from the measurement series, and $\Delta U_{max}$ a chosen value for the maximum rise in voltage magnitude. We will refer to the latter as the ”*worst-case voltage rise*”. The voltage after introduction of wind power is, at any moment in time, the sum of the voltage without wind power and the voltage rise due to the wind power. A distribution of the voltage after introduction of wind power is obtained by random sampling from the two time series:

$$U(k) = U_0(n) + \Delta U(m) \qquad (4)$$

where $U_0(n)$ is the time series of the pre-wind voltage magnitude; *n* and *m* are random samples from a uniform distribution over the whole measurement period of voltage and power, respectively. A total of one million random combinations of *n* and *m* were generated, thus resulting in one million values of the voltage magnitude. Note that the result is not a time-series of the voltage, as the correlation between consecutive voltage and power values has not been considered; neither has the correlation between voltage and power variations been considered. The resulting series $U(k)$ can however be used to obtain the probability distribution function of the voltage after the introduction of wind power. From this probability distribution, the 99%, 99.9%, 99.99% and maximum values have been calculated. The results are shown in Figure 4for a measured pre-wind voltage, as a function of the worst-case voltage rise. The worst-case voltage rise is proportional to the amount of installed wind power, as explained in the previous section, by (2). This figure is thus another representation of the well-known phenomenon that the risk of overvoltages increases with growing penetration of wind power, or other types of distributed generation.

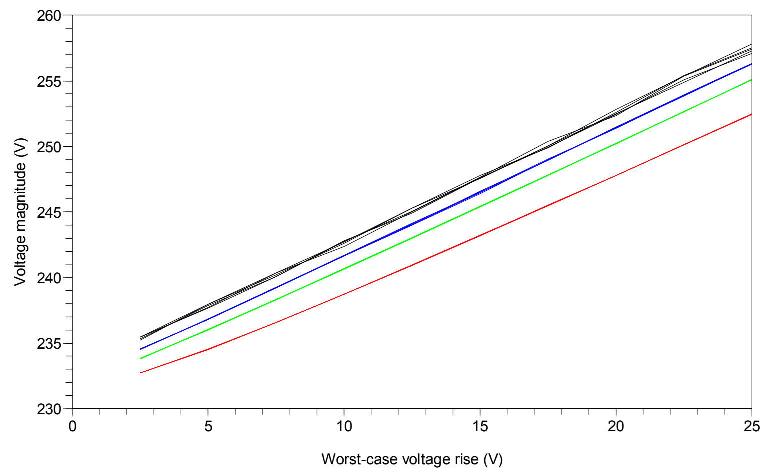



*Figure 4. Maximum value of the voltage magnitude as a function of the worst-case voltage rise: 100% (black), 99.99% (blue), 99.9% (green) and 99% (red).*

In the figure, five curves are shown for each of the indices (i.e. for each of the colours). These curves were obtained by using different series of random numbers and thus show the statistical uncertainty that is associated with Monte-Carlo simulations. For the 99% and 99.9% values the differences between the five curves is almost not visible; a minor difference is visible for the 99.99% values; a larger difference is visible for the 100% value. A much larger number of samples (than one million) are needed to get a good estimation of the 100% value from a Monte-Carlo simulation. Alternatively, and much faster, the maximum possible value (i.e. the 100% value over an infinite series) is obtained as the maximum pre-wind voltage plus the maximum voltage rise. The 100% value from the simulation will no longer be used in the further analysis of the results. It is only shown in Figure 4 for completeness.

## Statistical Voltage Rise

The statistical voltage rise is defined as the difference between a high percentile of the voltage magnitude and the maximum pre-wind voltage magnitude. This statistical voltage rise is shown in Figure 5 as a function of the worst-case voltage rise. For example: consider a worst-case voltage rise equal to 10 Volt: the deterministic voltage rise is based on the worst-case combination of maximum pre-wind voltage and maximum amount of wind-power production. This combination may however be very unlikely. Using the 99.9-percentile as a statistical indicator would result in a value of 7.5 Volt to be used to determine if the hosting capacity is exceeded. The use of the deterministic approach would limit the amount of wind power more than necessary; resulting in less wind power in the system or higher integration costs.

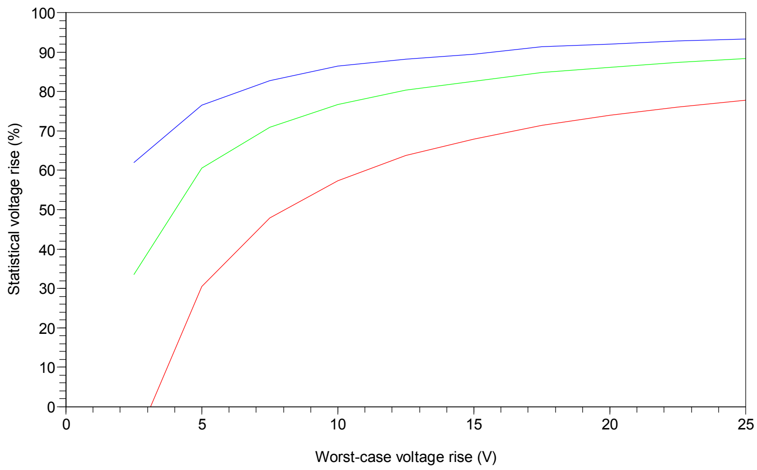



*Figure 5. Rise in voltage magnitude above the pre-wind maximum, as a fraction of the worst-case voltage rise: 99% (red), 99.9% (green) and 99.99% (blue) value of the voltage magnitude.*

## Comparison between different locations

The calculations resulting in Figure 5 have been repeated for 20 different time series obtained at 14 different locations. At three of the locations, voltages in the three phases were available; at the remaining 11 locations, only one phase was available. It was shown that the results for the three phases could be rather different, so that all time series were considered for the comparison. The voltage measurements were obtained over a several year period at locations around the world. There is no relation at all between those locations and the location at which the wind power production was measured. The aim of this paper has not been to estimate the hosting capacity at a specific location, but to illustrate the methodology.

The results for the 20 time series of voltage variations are shown in Figure 6, Figure 7, and Figure 8 for the 99, 99.9 and 99.99-percentile, respectively.

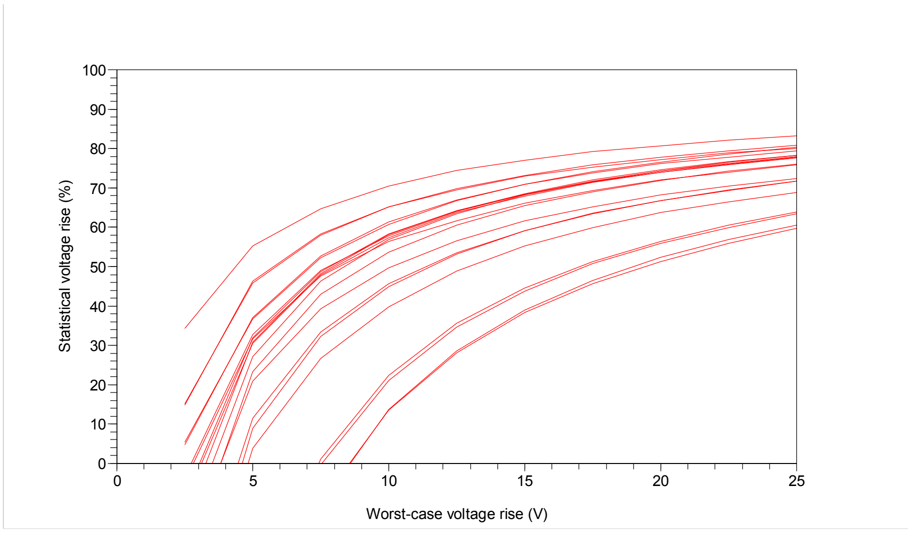



*Figure 6. Rise in voltage magnitude above the pre-wind maximum, as a fraction of the worst-case voltage rise: 99-percentile of the voltage magnitude; comparison between 20 different pre-wind voltage measurements.*

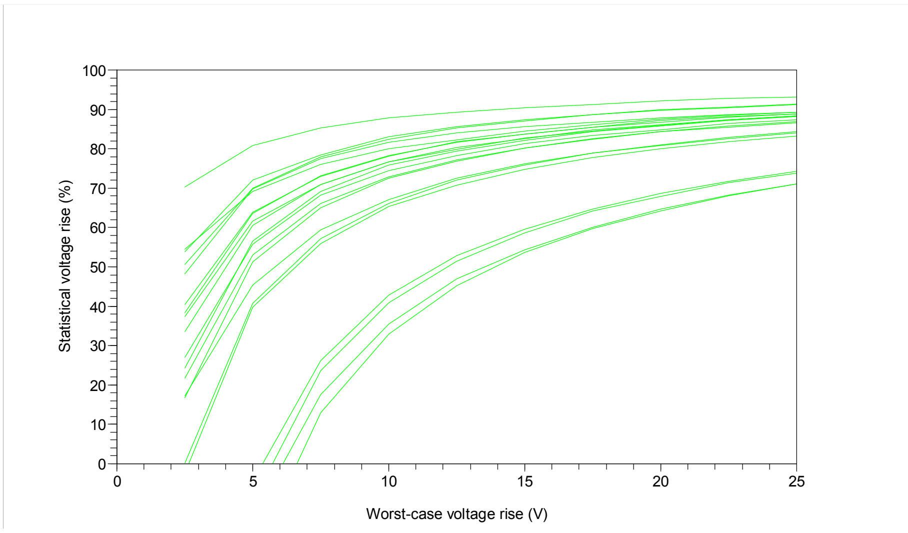



*Figure 7. Rise in voltage magnitude above the pre-wind maximum, as a fraction of the worst-case voltage rise: 99.9-percentile of the voltage magnitude; comparison between 20 different pre-wind voltage measurements.*

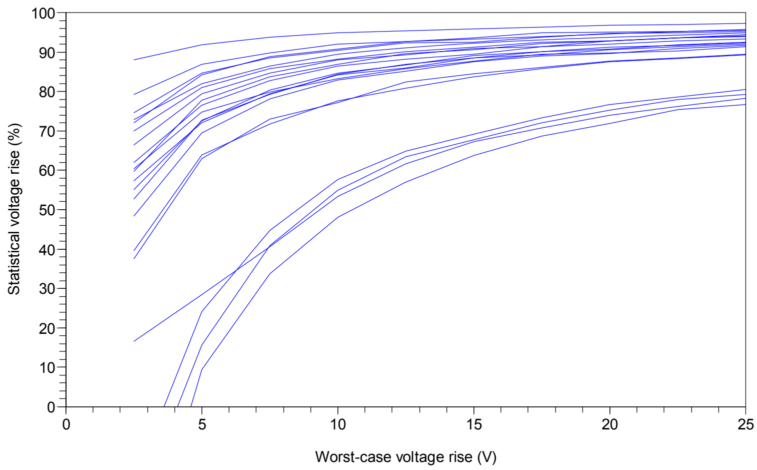



*Figure 8. Rise in voltage magnitude above the pre-wind maximum, as a fraction of the worst-case voltage rise: 99.99-percentile of the voltage magnitude; comparison between 20 different pre-wind voltage measurements.*

For all three figures, a group of four curves is clustered below the other curves. This implies that the statistical rise in voltage magnitude is less at these locations than at other locations. These four curves correspond to the three phases of location 1 and one phase at location 12. A closer look at the recordings (see Table 2) shows that the difference between the 99-percentile and the maximum of the pre-wind voltage magnitude is larger at these locations than at other locations.

The voltage rise due to the introduction of wind power is represented in a slightly different way in Figure 9, Figure 10, and Figure 11. The rise in voltage magnitude was defined earlier as the difference between a high-percentile value of the voltage when wind power is present and the maximum voltage without wind power. In the three figures below, the rise in voltage is defined as the difference in high-percentile value with and without wind power. The results are shown for the 99-percentile in Figure 9; for the 99.9-percentile in Figure 10, and for the 99.99-percentile in Figure 11.

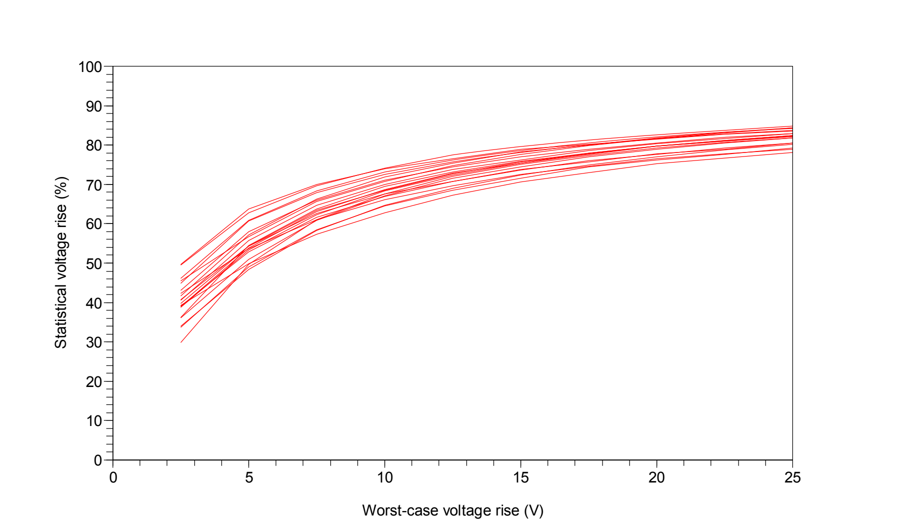



*Figure 9. Rise in 99-percentile of the voltage magnitude above its pre-wind value; as a fraction of the worst-case voltage rise; comparison between 20 pre-wind voltage measurements.*

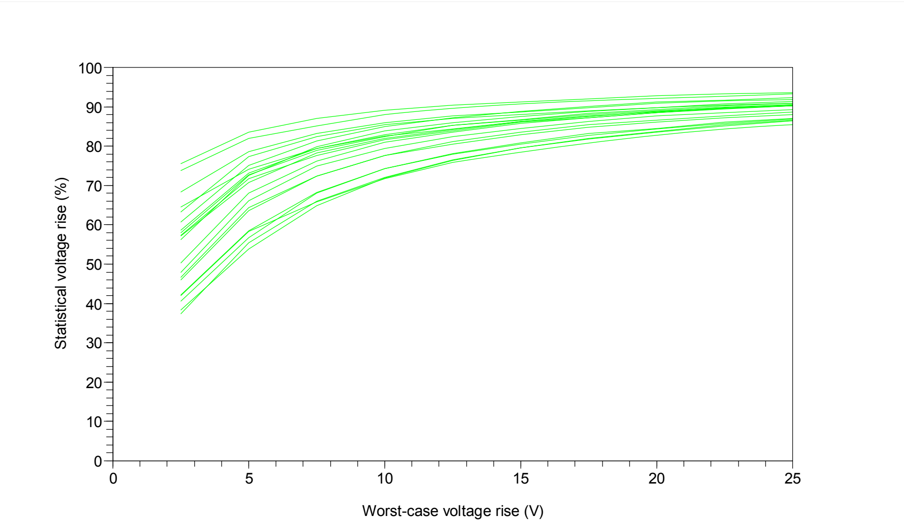



*Figure 10. Rise in 99.9-percentile of the voltage magnitude above its pre-wind value; as a fraction of the worst-case voltage rise; comparison between 20 pre-wind voltage measurements.*

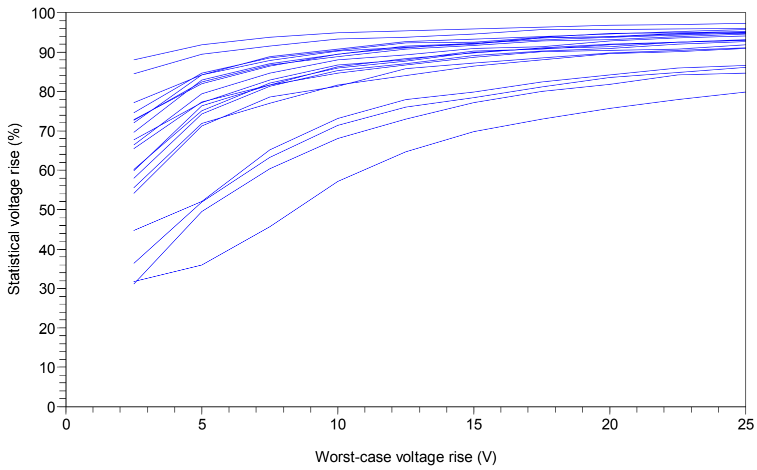



*Figure 11. Rise in 99.99-percentile of the voltage magnitude above its pre-wind value; as a fraction of the worst-case voltage rise; comparison between 20 pre-wind voltage measurements.*

The spread between the curves for different locations is reduced especially for the 99-percentile. For the 99-percentile value, it appears even possible to choose a curve that is representative for all locations. In that case the impact of wind power on the overvoltages may be estimated without doing detailed measurements or calculations. More studies are needed however before this can be confirmed.

## Voltage-Magnitude Variations

The difference in statistical voltage rise between the different locations depends on the different probability distributions of the voltage magnitude. Some of the statistical indicators of these distributions are shown in Table 2. As this paper concerns overvoltages, only information on high voltage magnitudes is included in the table. The table shows a large range of values, with maximum voltages between 98% and 106% of the nominal voltage. The difference between the 99-percentile and the maximum ranges from 0.4 to 5.5 V. This is illustrated in a different way in Figure 12, where the probability distribution function is shown in detail for high voltage magnitudes. The maximum value is used as a reference and the horizontal scale gives the voltage magnitude as compared to the maximum voltage. The step-like character of some of the curves is due to the limited voltage resolution of the instrument used for those measurements.

*Table 2. Statistics of the pre-wind voltage magnitude variations.*

| Location | 99-percentile | 99.9-percentile | 99.99-percentile | Maximum |
|---|---|---|---|---|
| 1 - phase a | 233.6 V | 235.1 V | 236.6 V | 238.4 V |
| 1 - phase b | 234.2 V | 235.8 V | 237.7 V | 239.7 V |
| 1 - phase c | 234.8 V | 236.2 V | 237.9 V | 239.3 V |
| 2 - phase a | 233.5 V | 234.5 V | 235.3 V | 235.7 V |
| 2 - phase b | 233.7 V | 234.8 V | 235.7 V | 236.1 V |
| 2 - phase c | 234.7 V | 235.7 V | 236.1 V | 236.4 V |
| 3 - phase a | 238.9 V | 239.8 V | 240.4 V | 240.6 V |
| 3 - phase b | 238.6 V | 239.3 V | 239.9 V | 240.1 V |
| 3 - phase c | 234.9 V | 235.5 V | 235.9 V | 235.9 V |
| 6 | 228.6 V | 228.9 V | 229.4 V | 229.4 V |
| 7 | 233.1 V | 233.5 V | 234.0 V | 234.3 V |
| 8 | 231.7 V | 232.4 V | 232.6 V | 233.0 V |
| 9 | 240.5 V | 241.1 V | 241.5 V | 241.5 V |
| 10 | 234.7 V | 235.1 V | 235.2 V | 235.4 V |
| 11 | 232.0 V | 233.4 V | 233.7 V | 233.9 V |
| 12 | 237.9 V | 239.4 V | 242.6 V | 243.0 V |
| 13 | 238.0 V | 238.2 V | 238.4 V | 238.4 V |
| 14 | 226.4 V | 227.0 V | 227.5 V | 227.5V |
| 15 | 233.5 V | 234.2 V | 234.9 V | 235.0 V |
| 16 | 225.5 V | 226.1 V | 226.4 V | 226.4 V |

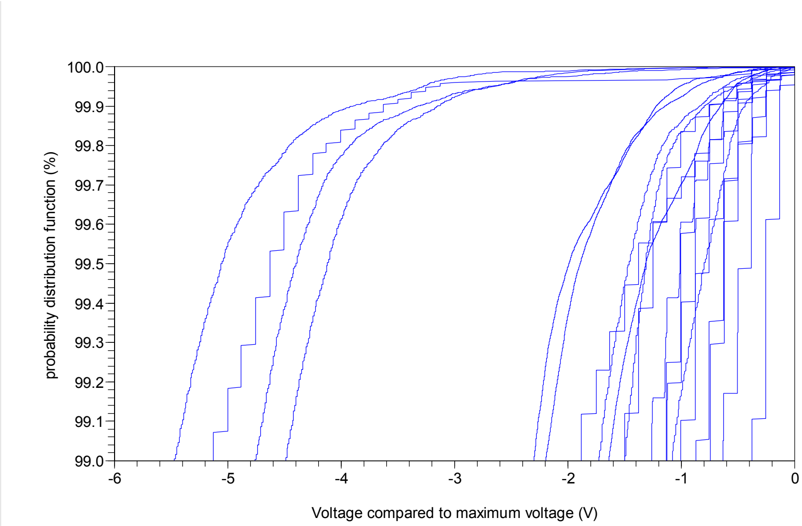



*Figure 12. Detail of the probability distribution function of the pre-fault voltage at all locations.*

## Conclusions

In this paper, the hosting-capacity approach has been applied to overvoltages in both a deterministic and a statistical way. The deterministic approach may be used when the amount of injected power is constant over time. However for highly fluctuating sources, like wind or sun, the deterministic approach could heavily overestimate the impact.

The result of using a deterministic limit by the network operator will be that less wind power is integrated in the network or that the integration costs become unnecessarily high. The need for connecting more wind power, to be able to reach the targets set by governments, makes it appropriate to further study statistical limits.

Both for deterministic and for statistical limits it is important that agreement is reached on suitable indices and objectives for overvoltages. The 10-minute 110% limit defined in EN 50160 may be used as a basis. Objectives for shorter-duration overvoltages (1 minute, 1 second) are also needed. The planning levels, used to determine the hosting capacity, should allow some margin compared to the requirements placed on the network operators.

However neither planning levels nor requirements set on the network operators should be such that they result in unnecessary barriers against the integration of more renewable sources of energy into the power system.

## Acknowledgement

Some of the measurements used for this paper were performed as part of the EU-DEEP project financially supported by the European Commission. Thanks are due to Fainan Hassan for critically commenting on the manuscript.

## Cover Picture

## Further reading

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