# PERFORMANCE INDICATORS FOR QUANTIFYING THE ABILITY OF THE GRID TO HOST RENEWABLE ELECTRICITY PRODUCTION

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## *ABSTRACT*

*This paper proposes a comprehensive set of performance indicators that should be used when evaluating the hosting capacity of a system. Descriptions are given for the most relevant phenomena and how they should be quantified and measured. The suggested time resolution for the data has been 1 hour, 10 min and 3 s, based on what is available already in standard meters. The use of 100, 99 or 95-percentile values have an impact on the hosting capacity, and there is a need for further discussion with regards to the selection of statistical limits.*

## INTRODUCTION

With the increasing amount of renewable energy sources (RES) throughout the power systems comes an increasing need of knowledge on whether this would lead to a deterioration of the system power quality to unacceptable levels. In this regard, the hosting capacity (HC) approach has been introduced in several studies as a means to quantify the generation capacity that can be connected to a network. The basic idea is that the maximum RES capacity that can be connected to the system is such that the system still operates satisfactorily [1, 2]. Unacceptable power quality can be caused by many different phenomena. In the context of this study, the impact of each phenomenon on the system power quality is quantified by one or more performance indicators. Performance indicators can be, for instance, disturbance levels of slow voltage variations, overloading, harmonics, flicker, rapid voltage changes, losses or the number of certain power-quality events in the network. The HC is set by the performance indicator resulting in the lowest amount possible to connect.

## PERFORMANCE INDICATORS

This section lists the most relevant performance indicators, along with details on how they can be quantified and measured.

### Overloading and overvoltages

Overloading and overvoltages are the most common indicators utilized to calculate the HC of a distribution system ([3], [4], [5] and [6] are some examples). It is generally accepted that RES relieve the network loading if the penetration level is low. However, high penetration levels of RES may reverse the power flow pattern, which, in turn, could lead to overloading of e.g. cables. The increasing production can also cause an unacceptable rise in voltage. The following performance indicators are identified for **overloading**:

#### Highest one-hour average current, average apparent power, and average active power, through the series component

The studies mentioned above make extensive use of data collected from meters as a one-hour average. Although one-hour average values may not capture temporary overloads that e.g. may lead to overload-protection tripping, it can still be considered an acceptable resolution for planning purposes. In some cases, measurements are not available for currents but only for active and reactive powers. Then, the performance indicator can be defined based on the apparent power instead. If only measurements for active power are available, the performance indicator can be defined based on active power. To estimate the current several assumptions can be made regarding the voltage. For instance, a conservative approach is that the voltages are assumed to be at the minimum acceptable level. However, it should be noted that this would give a pessimistic result regarding the HC.

#### Maximum temperature of the series component

In reality, the overheating will degrade the condition of the series component rather than the overcurrents themselves. However, based on the current, the component temperature can be estimated. Therefore, a temperature-based performance indicator can be defined. This is nevertheless a complex task, as it requires time series of the ambient temperature and other weather parameters. This indicator is only relevant when no or limited overload protection is present.

#### Loss of life of the series component

Temperatures above nominal conditions may cause degradation of the component lifetime. Thus the lifetime of the component can also be used as a performance indicator. The connection of a certain capacity of RES should only cause an acceptable decrease of the component lifetime. Also this indicator is only relevant when no or limited overload protection is present.

In order to use the above defined indicators for overloading, the following data is needed:

- Time series of the load profile. Multiyear data with a time resolution of at least one hour is needed.
- Time series of the expected production with the same resolution.
- Alternatively, time series of the current (or power) through the series component can be used. Then, the change of current (or power) introduced by the RES can be added to the pre-RES series component loading to assess the overloading indicator considering the RES.

### Probability of overload-protection tripping

From a customer perspective, overloading is only a concern if it leads to interruptions due to e.g. the tripping of overload-protection. Therefore, it is suggested to use the probability of overload-protection tripping as a performance indicator. This however requires a higher time resolution compared to the indicators in the previous section as well as information about the relays in use for the system under study.

For **overvoltages**, the following performance indicators are identified:

### 10-minute average value of the voltage

In the studies mentioned above, the voltage has typically been calculated as a result of a certain load and production scenario, whose data resolution is usually one hour. However, power quality standards such as EN 50160 or IEC 61000-4-30, suggests the use of the 10-minute average value for long-duration over- and undervoltages, and since this kind of data can be obtained from any class A meter, there is already plenty of data available. In order to use the above defined performance indicator, the following data is needed

- Time series of the load profile. Multiyear data with a resolution of at least 10-minutes is needed.
- Time series of the expected production with the same resolution as before.

Alternatively, voltage measurements can be used directly, preferably taken at the customer’s nodes. Then, the change in voltage introduced by the RES can be calculated using simplified expressions, like the ones found in [1].

Undervoltages are generally not a concern considering the connection of more RES. A possible exception is feeders with line-drop compensation in combination with unequal loading and/or amount of production on the different feeders [1].

## Losses

Losses are not considered a critical problem for the introduction of RES since they are not expected to increase dramatically beyond existing levels [2]. They are also not considered a major barrier from a cost or environmental point of view. However, according to [2] a detailed study of the system losses is needed in order to evaluate the economic impact on the network operation introduced by RES. References [1] and [2] derive the following expression for the decrease of losses due to the introduction of RES

$$\Delta\text{Loss} = \sum_{s=1}^{N_S} \int_0^T G_s(t)\left(2L_s(t) - G_s(t)\right)dt \qquad (1)$$

where $L_s(t)$ is the load through feeder $s$ and $G_s(t)$ is the generation through feeder $s$. If $2L_s(t) - G_s(t)$ is greater than zero, then the losses are decreased. From (1), assuming that the load and the generation patterns are not opposite to each other, the following condition is derived in [1] if no increase of losses is allowed

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

which limits the average production to twice the average existing load. The losses can be calculated along with an investigation of the HC with respect to overloading. Based on the above reasoning, the suggested performance indicator is the total annual losses per feeder or over the whole LV and/or MV network. The same data as the one utilized for the evaluation of the overloading (i.e. multiyear data on load and production) can be used. Observe that these data can also be used to evaluate (2).

## Fast voltage fluctuations

Fast voltage fluctuations can be divided into two areas which will be discussed separately:

- Continuous fluctuations in voltage, that may cause light flicker
- Fast and stepwise changes in voltage, referred to as rapid voltage changes

Flicker is usually quantified using the short- and long-term flicker indices $P_{st}$ and $P_{lt}$, which are defined in the flickermeter standard IEC 61000-4-15. The principle behind their calculation is a lamp-eye-brain model, based solely on a 60W incandescent lamp. However, this type of lamp is being replaced with more modern alternatives, which may be affected differently by continuous voltage fluctuations, and there is a lack of systematic studies in this area [7]. Nevertheless, the flicker levels are not expected to increase significantly with the introduction of RES [2, 8, 9], and the limits already in use in regulation such as EN 50160 (e.g. the 95th percentile of $P_{lt}$ should not exceed 1 during a week) are considered suitable for evaluating the HC.

Rapid voltage changes (RVCs) refer to stepwise changes in voltage (that do not exceed the voltage dip/swell thresholds). As is stated in IEC 61000-4-30:2015, RVCs are characterized by four parameters: start time, duration, maximum absolute difference in voltage during the event (based on half cycle rms values) and difference in steady state value before and after the event.

As a performance indicator, the number of events above a certain threshold (e.g. RVCs with a difference in steady state value above 2%) during a certain period (e.g. 24 hours) could be used. The time period and threshold to use can be based on pre-existing conditions in the network (i.e. the addition of RES should not cause a significant increase in RVCs of a certain magnitude).

## Medium scale voltage fluctuations

In the context of this paper, medium scale voltage fluctuations refer to voltage fluctuations in the time scale of 1 second to 10 minutes. While medium scale voltage fluctuations are a non-standardized phenomenon, it is expected that voltage variations in this time scale will increase as the amount of wind and solar power increases, as the produced power from these sources varies over a range of time scales.

Medium scale voltage fluctuations can be quantified using Very Short Variations (VSV) [10, 11, 12]. In brief, a 3-second VSV value, $\Delta U_{vs}$, is calculated as the difference between a 3-second value of the voltage, $U_{vs}$, and a 10-minute value, $U_{sh}$, according to

$$\Delta U_{vs}(t_k) = U_{vs}(t_k) - U_{sh}(t_k) \tag{3}$$

here $t_k$ is the time sample representing the end of a 10-minute interval. $U_{sh}$ is updated every new sample (i.e. a new 10-minute value is calculated every 3 seconds).

From the 3-second VSV, a 10-minute VSV value is then calculated according to

$$\Delta U_{sh}(t_k) = \sqrt{\frac{1}{N} \sum_{t=k-N+1}^{k} \Delta U_{vs}^2(t_i)} \tag{4}$$

where $N$ is the number of 3-second values in the 10-minute interval. Since IEC standard 61000-4-30 prescribes the use of 3-second and 10-minute values, any class A meter should be able to log data at the needed resolution (1- or 3-second values).

Another performance indicator could be the difference between the highest and lowest rms voltage recorded for every measurement interval (e.g. 10 min). Several measurement instruments have the possibility of storing such data.

It should be noted that limited research has been carried out with regards to voltage variations in this time scale and there is a need for more measurements in different kinds of grids, with a varying amount of renewables, in order to study how these voltage variations are affected by an increased penetration of solar and wind power.

## Voltage unbalance

Single phase connected RES, such as residential PV units, can lead to current unbalance if they are not uniformly distributed throughout the three phases of the system. Moreover, these current unbalances can lead to overvoltages with respect to the neutral in some of the phases [13]. The consequences of voltage unbalances include a decrease in efficiency and overheating in three-phase motors, and also unintended disconnection of three-phase converters [14]. There are several ways in which voltage unbalance can be quantified. As mentioned in [15], American standards often recommend the difference between phase amplitudes, while European standards recommend the use of symmetrical components. For instance, the negative sequence voltage is suggested in [1] as a performance indicator. The following is suggested in [1] to roughly calculate the impact of a number of single-phase units on the system negative sequence voltage

$$U_2 = \sqrt{\frac{N}{3}} \times \frac{P_{gen} \times Z_2}{U} \tag{5}$$

where $U_2$ is the negative sequence voltage, $N$ the number of single phase generators connected randomly to a three phase system, $P_{gen}$ the rated power of each unit, $Z_2$ the system negative impedance and $U$ the system nominal voltage. For a given limit of $U_2$, the number of units that can be connected can be estimated.

More investigations are needed regarding the impact of RES on system voltage unbalances. Measurements should be taken in areas with low and high penetration of single phase generators (such as residential PV) in order to characterize the voltages in each phase, as well as the sequence voltages, in the presence of RES. The results should be compared to the cases without RES in order to verify whether they cause a significant change in the unbalance level compared to the case without it. Note that three-phase connected RES may in fact increase the HC with regards to unbalance for single-phase connected RES, since they contribute to a smaller negative sequence source impedance. With regards to the time resolution used for unbalance, both 10-minute and 3-second values (as defined in IEC 61000-4-30) should be considered. For the thermal impact of unbalances 10-minute values are an appropriate indicator, whereas 3-second values are appropriate for unwanted disconnections of three-phase inverters.

## Harmonics

RES inject a certain level of harmonics into the system due to their type of interface (power electronics, for instance). Thus, a few works have considered the harmonic emission levels of RES as a performance indicator when quantifying the HC, where typically the Individual Harmonic Distortion (IHD) and the Total Harmonic Distortion (THD) have been used. An example where the IHD and THD are used is [16], where the harmonic distortion is considered in addition to thermal and voltage limits. The calculations performed in [16] show a decrease of the HC when harmonic constraints are included into the optimization problem. Other examples are [17] and [18], which introduce the following expression to estimate the harmonic HC

$$I_{HC}^h = \pm I_{sys}^h + \frac{V_{lim}^h}{Z_{sys}^h} \tag{6}$$

where $I_{HC}^h$ is the harmonic current HC, $I_{sys}^h$ the background current injection, $V_{lim}^h$ the harmonic distortion limit, and

$Z_{sys}^{h}$ the system harmonic impedance. The current $I_{sys}^{h}$ is calculated as the harmonic background voltage divided by the corresponding $Z_{sys}^{h}$. Note that in (6) an optimistic $I_{HC}^{h}$ is calculated with $+I_{sys}^{h}$, while with $-I_{sys}^{h}$ a pessimistic $I_{HC}^{h}$ is obtained. The expression above can be used to find the maximum harmonic current that can be injected by the RES, and hence its capacity.

Considering (6), the data needed to estimate the HC is:

- Individual current harmonic distortion from the RES unit.
- Measurements of the background harmonic voltage.
- Network models in order to calculate the system harmonic impedance.

In a similar manner to unbalance, both 10-minute and 3-second values of harmonics can be considered, depending on the focus of the study. For instance, when considering overheating of transformers, 10-minute values could be used whereas 3-second values can be used as a performance indicator considering undesirable trips of equipment.

While low-order harmonics (up to around 1 kHz) may not be an immediate concern with regards to the network performance when considering RES, the capacitance at the grid interface of such units may cause harmonic resonances or cause a shift in resonance frequencies to lower orders, where the emission is higher [19].

### Interharmonics

As is defined in IEC 61000-2-1, interharmonics refer to frequencies which are not an integer multiple of the fundamental. Levels used in regulation today for interharmonics tend to be low (IEC 61000-2-2 has a limit of only 0.2%, whereas EN 50160 has interharmonics “under consideration”). It has been proposed to allow higher levels, the reasoning being that higher limits for interharmonics will facilitate the connection of wind farms without significantly increasing the probability of adversely impacting other equipment [20].When considering interharmonics, the sub-group concept detailed in IEC 61000-4-7 could be used in the assessment, and the short term flicker index, $P_{st}$, could also be used as a performance indicator as one of the consequences of interharmonics is light flicker [21, 22]. However, more studies are needed to determine acceptable levels of interharmonics before they are used as a performance indicator when determining the HC.

### Supraharmonics

The term “Supraharmonics” refers to waveform distortion in the frequency range of 2-150 kHz (in a 50 Hz system). Research is ongoing in this field [23], and some work has been done in the frequency range 2 to 9 kHz. As an example, it is proposed in [24] to extend the existing standards on distortion to higher frequencies. However, [25] indicates that supraharmonics from different sources may cancel each other out to a much higher degree than is assumed in [24]. There is still limited knowledge about supraharmonics and how they originate and propagate, as well as their consequences. There are also several issues with regards to measurements of supraharmonics. As an example, conventional instrument transformers are generally not suitable for measurements in the frequency range in question, thus making it difficult to assess compliance in case eventual limits are defined.

There are examples of performance indicators for supraharmonics already in use, and discussions are taking place within standardization groups [26]. However, due to the issues stated above, more investigations are needed before supraharmonics can be applied as a performance indicator when evaluating the HC.

### Number of events

There has been some work on the use of the number of power quality events as a performance indicator, as well as the impact of RES on the number of events [1, 27, 28]. It should be noted that a fixed limit for the number of events applied across a system can, in fact, cause uncomfortable perception for existing customers. This is due to the fact that the defined limit might be higher than the already experienced number of events by the customer. Then, a considerable increase in the number of events produced by new RES, but still within the limits, will create discomfort for existing customers. This might lead to a customer refusal posture, creating a barrier for the installation of new RES. Instead, a performance indicator can be defined based on the already existing number of events.

One possible performance indicator could be the probability of overload-protection tripping, which is described in the section on overloading and overvoltages. The HC could then be evaluated with the requirement that the addition of RES should not cause a significant increase in the number of events due to the tripping of overload-protection.

## DISCUSSION

The definition of performance indicators has a significant impact on the resulting HC. For instance, parameters such as time resolution (e.g. 1 hour values, 10 minute values etc.) and percentiles (e.g. the index should not be exceeded 99% of the time as opposed to 100% of the time) used in the definition of the performance indicator can cause a considerable difference in the HC. As an example, [5] investigates overvoltages due to wind power. It is shown that based on the statistical overvoltage index used, the HC in the investigated system is 1 and 2.3 MW, for statistical overvoltage indices of 100 and 99%, respectively. In contrast, EN 50160, which is used throughout Europe, uses a statistical overvoltage value of 95%. There is a push for the use of 100% values in regulation, which may limit unnecessarily the amount of RES that can be connected.

Another important aspect when selecting performance indicators is how “performance” is defined. For example, it could mean compliance with standards or regulatory limits. Alternatively, it could mean a high probability of electromagnetic compatibility (i.e. a low probability of electromagnetic interference). Due to the on-going changes in power systems, including a large-scale introduction of RES, there will be an impact on emissions, immunity (e.g. the immunity of new equipment to voltage disturbances) and the transfer of disturbances [23], and new approaches to standardization may be needed.

## CONCLUSIONS

This paper has listed some typical phenomena that can limit the HC in a system and has given recommendations for suitable performance indicators for each phenomenon. Moreover, for most of the indicators described in this paper the suggested time resolution for the data has been 1 hour, 10 min and 3 s, since they are typical resolutions applied already in standard meters. Some indicators that are under investigation have been listed in this paper for the sake of stirring further discussion. In such cases, the reviewed studies have indicated the usefulness of continuous measurements in multiple locations.

There is a need for further discussion on the use of 100, 99 and 95-percentile values in regulation.

When evaluating the hosting capacity, alternative solutions such as curtailment should be considered as well.

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