Limits to the hosting capacity of the grid for equipment emitting high-frequency distortion

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Distributed energy resources (DER) have both positive and negative impacts on the operation of distribution networks. A large number of papers have been dedicated to this, with main emphasis on the voltage rise due to the injection of active power in the distribution grid. The impacts, concerning harmonics, are as follows:

a) Low-frequency distortion, up to 1 kHz, due to DER equipment, is not a concern for the performance of the network. The harmonic distortion of DER equipment is less than that of existing equipment like computers and televisions.
b) The capacitance at the interface to many DER units may cause harmonic resonances or shift resonance frequencies to lower values where the emission is higher.
c) High-frequency distortion, 1 kHz and higher, associated with the switching frequency are a concern for inverter-based DER.

This paper will discuss the latter issue: the injection of high-frequency distortion by DER units.

Low-frequency distortion (up to 1 or 2 kHz) is reasonably well understood and many papers plus a number of textbooks have been written that cover the subject, e.g. [1][2]. Waveform distortion for higher frequency is much less understood.

In this paper, an assessment will be made of the amount of DER that can be connected to the supply without exceeding reasonable levels of voltage distortion in the frequency range 2 to 9 kHz.

1 Hosting Capacity

To quantify the impact of increasing penetration of DER on the power system, the hosting-capacity approach has been developed [3]. 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.

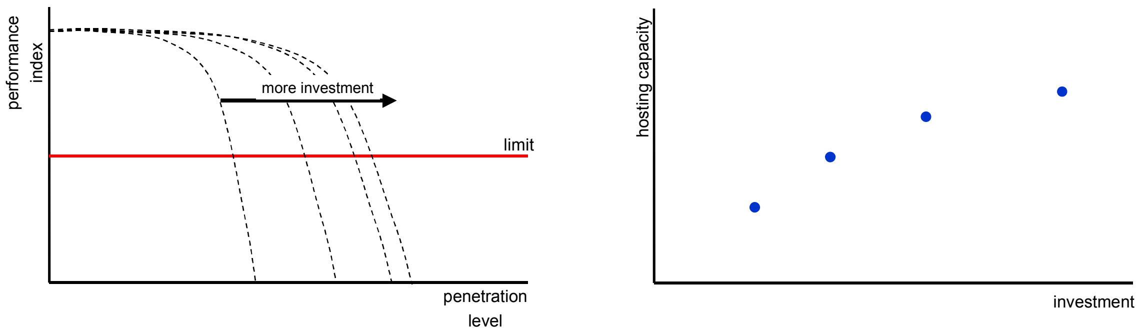

Fig. 1, performance index for the existing system and for increasing investment (left), with the hosting capacity being the penetration level at the intersection of a performance curve and the limit. The right-hand figure shows the hosting capacity as a function of the investment.

A hypothetical example of a hosting-capacity study is shown in Fig. 1: 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).

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).

2 LIMITS FOR HIGH-FREQUENCY HARMONICS

2.1 Performance indices

The characterization of harmonic distortion as defined in IEC standards includes harmonics up to order 40, i.e. 2 kHz in a 50-Hz system or 2.4 kHz in a 60-Hz system. Similarly to other documents harmonics above order 40 are not considered in this standard. An informative annex with IEC 61000-4-7 discusses a characterization method for disturbances in the frequency range 2 - 9 kHz. The lower limit of this frequency range is determined by the upper limit of the harmonic spectrum in a 50-Hz system. The upper limit is determined by the lower limit of radiated disturbances as defined in CISPR 16-1.

The standard document proposes to use a 100-ms window that no longer needs to be synchronized to the power-system frequency. The power-system frequency component should be removed through an analogue high-pass filter, so that leakage from the power-system frequency to higher frequencies no longer is a concern. Further, the disturbances in this higher frequency range are typically not linked to the power-system frequency but are due to active controllers that operate at a certain switching frequency. For the same reason there is no longer a need for separate protocols in 50-Hz and 60-Hz systems.

The frequency range of interest for these measurements is up to 9 kHz, so a higher sampling frequency should be used than that in the measurement of the harmonic distortion. A certain margin is needed between the highest frequency of interest and the Nyquist frequency. The sampling frequency for measurements in this frequency range should therefore be in the range 30 to 50 kHz. A switching frequency of 40.96 kHz appears a rather convenient choice as it results in $4096 = 2^{12}$ samples per 100-ms window. This allows for the use of the computationally efficient fast-Fourier transform algorithm.

Measurements in this frequency range thus require analogue filtering both on low-frequency and on high-frequency side. A high-pass filter is needed to remove the fundamental frequency and some of the lower-order harmonics. A suitable stop-band edge is slightly above the 7:th or 9:th harmonic. Analogue filtering is needed here so that the whole dynamic range of the analogue-digital converter can be used for the high-frequency component. A low-pass filter is needed to prevent aliasing. The pass-band edge should be above 9 kHz. For a 40 kHz sampling frequency, the stop-band edge should be less than 31 kHz. The filter requirements are summarized in Fig. 2.

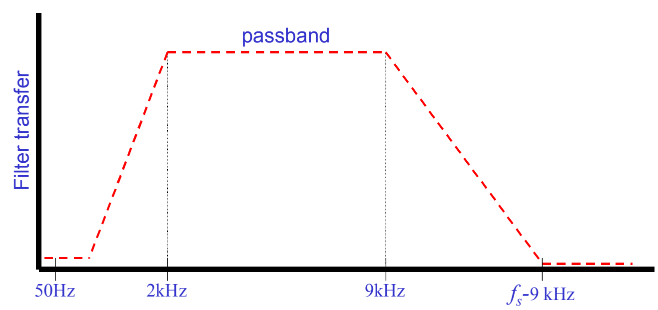

Fig. 2, Analogue filter requirements for measurements in the frequency range 2 - 9 kHz.

Applying a discrete-Fourier transform (DFT) algorithm to the 100-ms window results in frequency values with 10-Hz separation. The resulting values are grouped into 200-Hz bands, using the following grouping algorithm:

$$G_b = \sqrt{\sum_{f=b-90Hz}^{b+100Hz} C_f^{\ 2}} \tag{1}$$

with C_f the rms value of the frequency component at frequency f. This grouping algorithm results in 35 frequency bands centered around 2100, 2300, ... , 8700 and 8900 Hz.

2.2 Compatibility above and below 2 kHz

The choice of frequency bands is based on CISPR 16-1, where the same 200-Hz bandwidth is used for measurement of radiated disturbances. The characterization method is however not compatible with the method used for harmonic and interharmonic distortion. The grouping algorithms for harmonics and interharmonics, as described in IEC 61000-4-7, add the signal energy of all frequency components within each group of subgroup. The grouping algorithm used in the frequency band 2 - 9 kHz, also adds the energy over all components within each frequency band but over a different frequency band. For a single-frequency signal (a line spectrum) the result will be consistent for both methods. Thus a 1 Volt signal at 2 kHz will result in a 1 Volt value for the 40:th harmonic, as well as a 1 Volt value for the 2100-Hz band.

The situation is different for broadband signals, the kind of signals that are more common for the higher frequency ranges. To compare different frequency bands it is important to consider Parseval's theorem. Parseval's theorem relates the energy of the signal in time domain and in frequency domain. For digital (sampled) signals Parseval's theorem reads as:

$$\frac{1}{N}\sum_{i=1}^{N}\{g(t_i)\}^2 = \sum_{k=0}^{N/2}|C_k|^2 \quad (2)$$

The left hand side is the square of the rms value of the signal, which is independent of sampling rate or measurement window. Doubling the measurement window will double the number of frequency components. For a broadband spectrum the energy will be spread over the frequency components, so that the amplitude of each component will be reduced by a factor of square-root two. The basic frequency components below 2 kHz are obtained from a 200-ms window; the ones above 2 kHz from a 100-ms window. Let the amplitude of a 5-Hz component (obtained from a 200-ms window) be equal to 1. The amplitude of a 10-Hz component (obtained from a 100-ms window) is then equal to $\sqrt{2} \approx 1.41$ and the amplitude of a 200-Hz band is equal to $\sqrt{40} \approx 6.32$. All this assumes a flat continuous spectrum within the 200-Hz frequency band. Table I gives the resulting amplitudes for the harmonic and interharmonic groups and subgroups in a 50-Hz and 60-Hz system when the 200-Hz band results in a value of 1 Volt. See IEC 61000-4-7 for the definition of harmonic groups and subgroups.

TABLE I
RELATION BETWEEN AMPLITUDE OF GROUPS AND SUBGROUPS FOR A FLAT CONTINUOUS SPECTRUM WHEN THE 200-HZ BAND RESULTS IN A VALUE OF 1 VOLT.

	50 Hz	60 Hz
Harmonic Group	0.5 V	0.55 V
Harmonic Subgroup	0.27 V	0.27 V
Interharmonic Group	0.47 V	0.52 V
Interharmonic Subgroup	0.42 V	0.47 V

2.3 Performance limits

As shown in the previous section, the distortion levels in the range 2-9 kHz cannot be immediately compared with the levels for lower frequencies (harmonics 2 through 39). Harmonics are treated as predominantly a line spectrum superimposed on a continuous spectrum. In IEC 61000-4-7 harmonic and interharmonic groups and subgroups are defined to separate the harmonic spectral lines from the rest of the distortion.

In the frequency range of 2-9 kHz the spectrum is treated as a continuous spectrum. The energy in every 200-Hz band is used as a performance index. Note that there is no sharp transition between a line spectrum and a continuous spectrum at 2 kHz. The actual change is smoother and may start already at 1 kHz. However the change in analysis methods is chosen, somewhat arbitrarily at 2 kHz.

To compare the levels and limits below and above 2 kHz the values in Table I should be used. Limits for harmonic distortion are given in a number of documents: voltage characteristics for low and medium-voltage networks are given in EN 50160 up to harmonic 25; compatibility levels for low-voltage networks are given in IEC 61000-2-2; indicative planning levels for medium and high-voltage networks are given in IEC 61000-3-6. The latter documents include harmonics up to order 40.

It was decided to use the planning levels in IEC 61000-3-6 as a basis for the hosting-capacity approach. The setting of limits for the connection of DER units is viewed as a design issue for which planning levels should be used. Further are no voltage characteristics available above harmonic order 25. As the voltage characteristics are the same for low and medium-voltage networks, it was decided to also use the same planning levels for low and medium-voltage networks.

The following reasoning has been followed to obtain the limits in the frequency range of 2-9 kHz:

- The limits in IEC 61000-3-6 for the highest even and triplen harmonics are 0.2%.
- The limits for odd harmonics decay towards 0.2% inversely proportional to the frequency. The indicative planning level for the 40:th harmonic is 0.8%.
- According to IEC 61000-4-30, the harmonic subgroups should be used to characterize harmonic distortion.
- According to Table I, a level of 0.2% for the harmonic subgroup corresponds to a level of $\frac{0.2}{0.27} = 0.74\%$ for the 200-Hz band.
- The limit for interharmonics is 0.2%.
- According to IEC 61000-4-30, the interharmonic subgroup shall be used to characterize interharmonic distortion.
- According to Table I, a level of 0.2% for the interharmonic subgroup corresponds to a level of $\frac{0.2}{0.47} = 0.43\%$ for the 200-Hz band.
- The distortion in the 2-9 kHz range consists of high-order harmonics associated with distortion of the 50-Hz waveform (especially at non-triplen odd harmonics) and components associated with the switching frequency of the active converters. The former component will be limited by the limits for lower-frequency components. The main concern is the distortion due to active converters, which will most likely not be synchronized to the power-system frequency.
- The proposed limit (in the hosting-capacity approach) for the 2-9 kHz range is 0.5% for each 200-Hz band.

This reasoning is admittedly incomplete but is probably the most that can be achieved at this moment. The aim of the study described in this paper is not to set harmonic-distortion limits, but to estimate the hosting capacity.

3 EMISSION BY DER UNITS

3.1 Individual DER units

The harmonic spectrum of converters applied by distributed energy resources (DER) is filled with sub- and interharmonics beside the characteristic harmonics. This spectrum can vary during the fundamental period and depend on the generated power. Moreover, the harmonic content may also be influenced by the background harmonics and the unbalance of the power network.

Standards and most publications limit themselves to harmonic emission levels up to 2 kHz. The amount of information on expected emission in the frequency range 2 kHz and higher is very limited.

A number of measurements performed elsewhere have been compared. The measured distortion per 200-Hz group has been summarized in Table II. The two deviating results are a laboratory setup and a DFIG inverter. From the other results it is concluded that the distortion is between 1 and 5%. It is unclear if the laboratory result is simply a better design or that the lower current distortion is due to the cleaner background voltage. Based on the information in the table, it was decided to use a current distortion between 1 and 3% for small single-phase units and between 0.5 and 1.5% for larger three-phase units.

TABLE II
OVERVIEW OF MEASURED CURRENT DISTORTION.

Estimated 200-Hz group current	Description
1.5%	2250-W PV inverter [4]
0.3%	Laboratory setup aimed at limiting harmonic current distortion. [5]
12%	DFIG inverter. The base current is the inverter current. A lower distortion index is obtained when the total current of the wind turbine is used as a base. [6]
3.3%	100-kW microturbine [7]
5%	110-W PV inverter [8]
2.4%	150-W PV inverter [9]
3.1%	100-kW PV system [10]

3.2 Multiple inverters

When inverters for DER are connected to a cluster, the converters do affect each other. The degree of the interaction depends on the type of the converter, above all the applied switching technique, and for converters with hysteresis current control the individual load. The harmonic generation of inverters is affected by the attenuation and the diversity effects at the point-of-common coupling (PCC).

The attenuation effect is related to the short circuit ratio at the PCC and often neglected in the modeling. The current distortion decreases meanwhile the voltage distortion increases with increased number of inverters. The diversity effect leads to a reduced vector sum of the actual harmonic order at the PCC, which is advantageous. Diversity increases with the frequency.

The diversity effect can be handled mathematically by the following ways:

- i Simple summation laws
- ii Monte Carlo method
- iii Probabilistic investigation.

Two simple summation laws can be applied in absence of detailed information about the converters: the linear summation law for low harmonic orders and the square-root summation law for higher harmonic orders. They are easy to use, but their results are less reliable than the other - more advanced - methods. The analytical probabilistic formulation of random harmonics is a very effective method when applicable and can be indispensable to the interpretation of the obtained simulation results. However, the method is often limited to cases with limited complexity. The Monte Carlo simulation is the most practical method to solve complex problems involving random variables. The most effective solution is based on a combination of the flexible Monte Carlo method and the very fast analytical probabilistic approach.

The application of the above methods has been demonstrated by case studies. It was also shown that

i The analytical method can be used for five or more converters

ii The square-root summation law gives the same result as the analytical method for summation of random signals at 95% probability level.

The summation methods can also be applied for inverters located at different PCCs by taking into account the harmonic propagation.

4 Estimating the Hosting Capacity

4.1 Methodology

In order to easily estimate the maximum allowable harmonic voltage emission level from the harmonic current limits (or vice versa), information about the harmonic network impedance is needed. This impedance is usually calculated from simulations of the harmonic power network or directly accessible from measurements.

The harmonic network impedance varies considerably between the nodes of a power network and also during the day. Measuring results are available for the LV network in the frequency range 2-9 kHz in [11]. According to the measurements the impedances were higher in overhead systems than in cable systems by a factor 3-5. The ratio of “phase-to-phase” impedance to “phase-to-neutral” impedance was in range of 1.5-2. The 90-95% probability curve of the phase-to-neutral impedance is approximated as:

$$Z(f) = \frac{f}{1000} + 1 \quad (3)$$

where f is given in Hz and the impedance in Ohm. For example the phase-to-neutral impedance in the LV network at 5 kHz is below 6 ohm for 90-95% of connection points.

When both the harmonic current spectrum of an inverter and the allowed voltage emission level at the PCC are known at a considered frequency then the hosting capacity of the same type of inverters can be estimated by utilizing the square-root summation law according to which the current distortion is proportional to the square-root of the number of units. This summation law was shown to correspond well with the results from accurate calculations for random signals at 95% probability level.

The harmonic voltage level due to a single inverter with relative harmonic current I_{nrel} at harmonic order n:

$$V_n = Z_n I_{nrel} I_{nom} \quad (4)$$

where Z_n is the network impedance at harmonic order n and I_{nom} is the nominal current. For N identical inverters with non-correlated harmonic currents and harmonic orders n>10 (random signals) the attenuated harmonic voltage at the PCC is:

$$V_{nN} = \sqrt{N} \times V_n = \sqrt{N} \times Z_n I_{nrel} I_{nom} \quad (5)$$

By supposing that the attenuated harmonic voltage V_{nN} is equal to the maximum permissible voltage emission level E_{nrel} at harmonic order n and nominal phase voltage U_{nom}, the hosting capacity can be calculated:

$$N = \left(\frac{E_{nrel} U_{nom}}{Z_n I_{nrel} I_{nom}} \right)^2 \quad (6)$$

For the LV network and frequency band 2-9 kHz (harmonic orders n from 40 to 180) this equation can be written as:

$$N \approx \left(\frac{E_{nrel} U_{nom}}{(0.05n + 1) I_{nrel} I_{nom}} \right)^2 \quad (7)$$

The value of N is at its lowest value when $Z_n I_{nrel}$ has its maximum, where Z_n is the "reference impedance" as in (3). The frequency at which this occurs is the "critical frequency" for the hosting capacity, i.e. the voltage-distortion limit will be exceeded first at this frequency. In the fortcoming sections, the hosting capacity is calculated as a function of this frequency.

From the discussion on performance indices and limits in Section III, a limit of E_{nrel}=0.5% was concluded for the voltage distortion per 200-Hz group. This value, together with the values for the current distortion per 200-Hz group can be used to estimate the hosting capacity.

4.2 Single-Phase Units

Consider as an example a 1-kW, 230-V, single-phase unit (I_{nom} = 4.34 A). The resulting hosting capacity is shown in Fig. 3 as a function of the critical frequency. The current distortion at the critical frequency was assumed to be between 1% and 3% for individual units. The decrease in hosting capacity with frequency is due to the linear increase in source impedance with frequency.

For a 1% current distortion (per 200-Hz group) the hosting capacity is more than 50 around 2 kHz but decreases to less than 10 around 9 kHz. For higher current distortion the hosting capacity becomes close to unity, implying that even one single unit would result in voltage distortion close to or exceeding the acceptable limit.

The decrease in hosting capacity with frequency makes that especially the distortion at higher frequencies should be damped to obtain an appropriate hosting capacity.

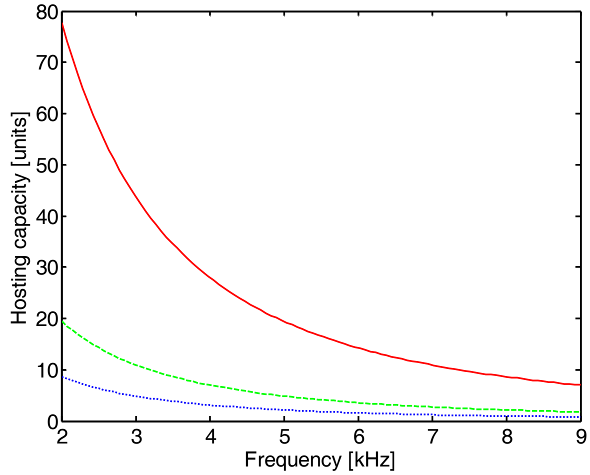

Fig. 3, 1-kW single-phase units for current distortion of 1% (red, solid), 2% (green, dashed) and 3% (blue, dotted).

4.3 Three-Phase Units

The calculations have been repeated for a 10-kW three-phase unit (I_{nom} = 25 A). The current distortion for such a unit is assumed to be between 0.5% and 1.5%. It appears reasonable that for a larger unit more investment in filtering and switching technology is economically feasible in order to reduce the distortion. The results are shown in Fig. 4. Even for those reduced distortion values, the connection of two units close together is not always possible.

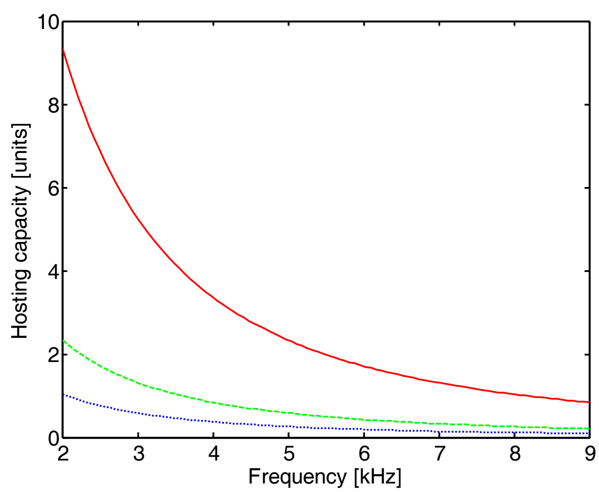

Fig. 4, 10-kW three-phase units for current distortion of 0.5% (red, solid), 1% (green, dashed) and 1.5% (blue, dotted).

For a 1% current distortion (per 200-Hz group) the hosting capacity for single-phase units is more than 50 around 2 kHz but decreases to less than 10 around 9 kHz. For higher current distortion the hosting capacity becomes close to unity, implying that even one single unit would result in voltage distortion close to the acceptable limit.

It is important to note that the source impedance used in the calculations is the upper limit value for 90 to 95% of locations. Thus the hosting capacity is even less than the value given here for 5 to 10% of locations. It should also be noted that random phase between the individual sources is assumed. It remains unclear if this is a correct model for DER inverters. When correlation exists the distortion of multiple inverters may be higher and the hosting capacity less.

Even for reduced distortion values assumed for three-phase units, the connection of two units close together is not always possible.

5 FLUORESCENT LAMPS WITH HF BALLAST

The same reasoning as used for DER unit can be applied to other sources of high-frequency distortion. High frequency fluorescent lamps are known to emit signals due to active switching [12]. A measurement on both the voltage and the current drawn by one to nine lamps connected to one phase has been carried out in the Pehr Högström Laboratory at EMC-on-Site. The results are shown in Fig. 5 and Fig. 6. The 200-Hz spectrum from 2-9 kHz is shown in Fig. 5. The figure shows how the spectrum changes with the number of lamps turned on. The voltage is calculated by multiplying the measured current with the "reference impedance" Z_n in (3) and normalized with the assumption of 230-V RMS at fundamental. Many of the 200-Hz bands increase in value with the number of lamps being turned but from around 5 kHz and up there is no increase with the number of lamps. The change in current spectrum with increasing number of lamps is discussed in further detail in [12].

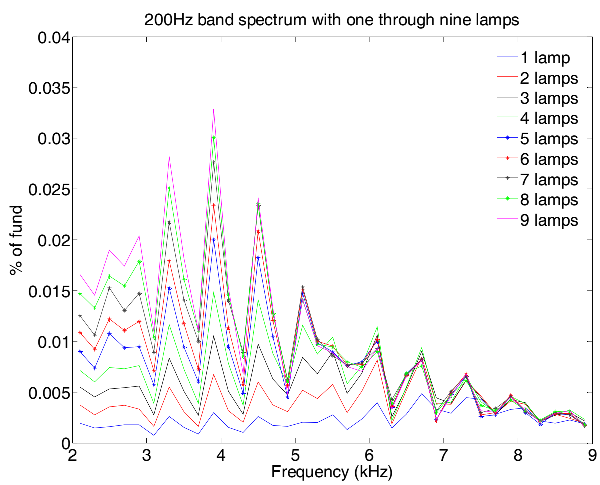

Fig. 5 The spectrum from 2 to 9 kHz with one to nine lamps.

The result in presented in a different way in Fig. 6. The amplitude of the voltage distortion is plotted as a function of the number of lamps for each of the 35 200-Hz bands in the frequency range 2-9 kHz. Of importance for the hosting-capacity approach is the highest value of any of the 200-Hz bands as it is this one that first reaches the performance limit. From the figure the approximation is made that the highest value increases linearly with the number of lamps.

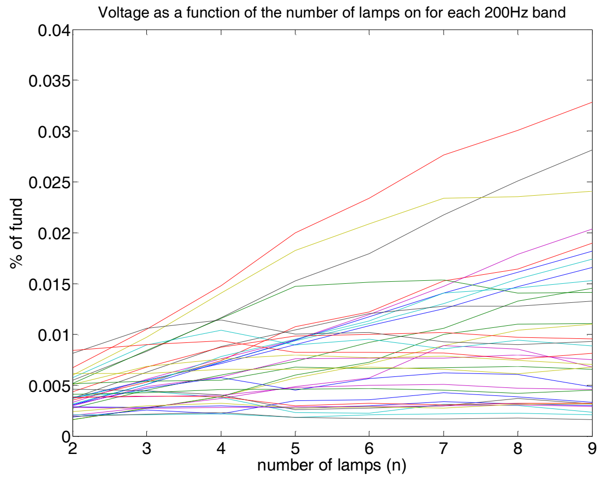

Fig. 6 The 35 200-Hz bands as a function of the number of lamps

Using the same notation as for DER unit, this reads as:

$$V_{nN} = 0.0037 \times N \quad (8)$$

The limit is equal to 0.5% so that the hosting capacity is reached for

$$N = \frac{0.5}{0.0037} = 135 \quad (9)$$

The hosting capacity of the network for this type of fluorescent lamps is thus equal to 135 lamps.

6 Conclusions

The hosting capacity has been calculated for DER units by combining the following information:

- The emission (current distortion) from one individual unit.
- A square-root summation law to obtain the emission from multiple units.
- A reference source impedance not exceeded for 95% of locations.
- Voltage distortion limits.

The result varies between 80 and 2 for 1-kW single-phase units and between 9 and less than one for 10-kW three-phase units, depending on the emission level for which the most severe distortion occurs. This result calls for a serious discussion on emission limits for DER units and/or on acceptable voltage-distortion levels between 2 and 9 kHz.

Typical emission levels were obtained by taking the levels of existing equipment from a number of sources. No attempt was made to determine emission limits that would be achievable for reasonable costs.

A simple square-root summation law has been used, assuming random phase for all frequency components. No information is available on the actual summation of the emission from DER units. Frequency components that increase faster than according to the square-root law, will dominate for larger penetration levels and further reduce the hosting capacity. Further studies (both simulations and measurements) are urgently needed to obtain appropriate summation laws. The small values of hosting capacity, around unity, will however not be affected by the summation law.

A related question concerns the spread in distortion through the network. In other words: how close should two units be so as the count towards the same hosting capacity. In this paper it has been assumed that all units are connected at the same location, which will rarely be the case in reality.

The calculations have been repeated for fluorescent lamps with high-frequency ballast. Measurements showed that the distortion in the 2-9 kHz band increases linearly with the number of lamps. The resulting hosting capacity for this kind of lamps was estimated as about 130 lamps. The large value of the hosting capacity makes that the summation law used will have a huge influence on the results.

The voltage distortion limits used in this paper are based on the planning levels for harmonics below 2 kHz. Using the higher objectives from EN 50160 would result in a hosting capacity that is a factor 2 to 5 higher. This discussion should be part of a general discussion on acceptable voltage-distortion levels in the frequency range 2-9 kHz. The methodology presented in this paper could be used to coordinate emission and voltage-distortion limits. The discussion should further include the possible adverse effects of increased distortion in this frequency range.

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