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Some Thoughts about Harmonic Limits in Connection Agreements for Wind Power Plants

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Abstract. For the connection of wind power plants into the public grid there are power quality procedures and limits that need to be complied with. The direct aim of those is to ensure a suitable power quality in the grid, but to ultimate aim is to ensure a high probability of electromagnetic compatibility. Each country has different requirements and standards, and with this, different procedures. In this paper, an overview of these methods will be given, together with some of the advantages and disadvantages. Furthermore, a review of the modifications regarding the latest versions of IEEE 519-1992 and IEC 61000-3-6 will be presented.

Key words

Power Quality, Electromagnetic Compatibility, Grid Codes, Harmonic Limits, Harmonic, Wind Power Plants

1. Introduction

The power quality is an important factor in studies that aim to investigate the impact that different energy sources, such as wind power plants (WPPs), cause with their connection to the public grid. Harmonics are one of the power quality concerns, because they can cause excessive heating in motors and generators, increases heating and voltage stress in capacitors and misoperation in electronics. Harmonic studies are a common part of the studies before the connection of a WPP to the electric power grid. The ultimate reason for performing such studies is to avoid interference between the grid and equipment connected to the grid. That equipment includes equipment in the WPPs, as well as equipment connected elsewhere. The studies do, however, rarely address actual cases of interference; but instead harmonic voltages and/or currents after connection are compared with limits provided by the network operator or set in standards or regulations.

Different compliance procedures exist in different countries and between different network operators within a country. Some of the limits do not depend on location, others related to voltage distortion allocation and fault levels. Due to this diversity of procedures, we will present a summary of those methods with some of the advantages and disadvantages. Those advantages and disadvantages will be discussed from the viewpoint of different stakeholders, especially for the network operator and for the owner or operator of the WPP.

2. Location Independent Limits

For mass-produced low-voltage equipment it is common to have the same emission limits for any device (of a specific type) independently of where it is connected to the grid. A television used in the center of a city (where the grid is strong) needs to comply with the same harmonic emission limits as a television used in a remote part of the countryside (where the grid is weak). Such limits for small equipment are given in IEC 61000-3-2.

This is in fact the approach used in IEEE Std. 519 [1], where the same emission limits hold for any production unit, no matter how weak or strong the grid is. In the case of [1], the limits apply to the complete installation, not to individual turbines. The recommended values in IEEE Std. 519, are based on the fact that some level of voltage distortion is generally acceptable and both system owners/operators and users must work cooperatively to keep the voltage distortion below the limits [2].

The big advantage of this approach is that the setting of the limits is simple. No information at all is needed about how strong the grid is at the point of connection. The limits for even harmonics are rather strict in [1] and plants may have difficulties in complying with them. Even in cases when there is no risk of high harmonic voltage distortion at those frequencies, there is still the need to limit emission to rather low values. A disadvantage from the network operator viewpoint is that even in case of high harmonic source impedance at the point of connection, no additional requirements can be placed on the WPP. This could especially be an issue in networks with high-voltage cables and resonance frequencies close to low-order harmonics.

3. Voltage Distortion Allocation

The fundamental idea behind disturbance allocation is that each customer, or group of customers, is allowed to cause a certain voltage distortion. The arithmetic sum of all the contributions can be more than the planning level, based on the so-called aggregation rule used (see below). Once the allocation is made, it is each customer's responsibility to remain within its allocation, whereas the network operator carries the risk that the allocation rule is too generous towards the customers. Examples of allocation rules are discussed in [8] and [9].

This allocation depends on the existing voltage distortion (the "background distortion") and assumes certain aggregation rules. This way, the allocation will be strongly location dependent. The current emission limit is determined from the voltage distortion allocation and the local source impedance as a function of frequency. The method gives a good estimation of the actual amount of voltage distortion that the WPP is allowed to cause before acceptable limits are exceeded. The main idea is to ensure that the harmonic voltage level at each bus remains no higher than the planning level. To ensure that the allocation is equitable in some sense, allocated harmonic emission level should be an increasing function of load magnitude [5]. The basic information is the forecasts of power flows taking account of the system evolution in the future [3].

For the aggregation, TR/IEC 61000-3-6 presents a general summation law for each harmonic order (h), as presented in (1). The recommended summation exponents are presented at Table I.

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \tag{1}$$

Where U_h is the magnitude of the resulting harmonic voltage (order h); U_{hi} is the magnitude of the various individual emission levels (order h) to be combined; α is a summation exponent.

Table I – Summation Exponent for Harmonic Aggregation Calculation [3]

Harmonic Order	α
h < 5	1
5 ≤ h ≤ 10	1.4
h > 10	2

Another important topic is the aggregation between turbines and the aggregation between existing and future customers. However, these are not always considered in the studies. For the aggregation between the turbines, most of the time, the network operator does not pay attention to this factor. However, due to the different aggregations that can occur inside the WPP, this type should be addressed. The aggregation exponents as in Table I are also regularly used for this. Here it should however be noted that these exponents were never intended for emission studied but only as a method for allocation of voltage distortion. Some studies have been made of the actual aggregation between individual turbines [10,11] and these show that reality is far more complicated than the simple aggregation rule. For the aggregation between existing and future customers (WPPs), as this is a statistical situation, an "uncertain uncertainty" problem appears, especially in countries where this situation is not considered and the whole margin is given to the first wind park that wants to connect, making it impossible or difficult to connect future installations.

The use of this approach is in the advantage of both the network operator (limited risk of high voltage distortion) and of the WPP owner (no unnecessary severe limits). Detailed studies are needed especially those to obtain the source impedance as a function of frequency. Allocation is based on certain simplified models for aggregation between customers. It is not clear if those models are an accurate representation of reality.

4. From Voltage Allocation to Current Limit

One a certain amount of voltage distortion has been allocated to a customer, current emission limits can be set in a number of ways. Most methods are one way or the other an application of Ohms' law, calculating a current from a voltage, using an impedance. The difference between the methods is in the choice of this impedance. Some options are:

- A fixed impedance versus frequency, for all locations.
- An impedance versus frequency dependent only on the fault-level at 50 Hz.
- The actual (or accurately calculated) impedance versus frequency.

Then there is the method where the actual change in voltage distortion before and after connection is the criterion used. All the other methods only consider primary emission whereas this last method considers primary and secondary emission [12, 13]

The second and third method need to consider the different operational states of the system. When only normal (strong) operational states are considered the emission requirements are much lighter than when only abnormal (weak) operational states are considered. Recommendations for the selection of states are given in IEC 61000-3-6, where it is for example sufficient to consider the operational states that cover 95% of time.

5. Limits Depending on Fault Level

A way to diversify between weak and strong grids is to make the emission limits depending on the fault level (short-circuit impedance) at the point of connection. The current emission limit could be chosen as linear with the fault level; the result would be the same harmonic voltage allocation for each location. According to [3], this case can be used for the connection of small installations or installations with limited amount of distorting equipment. For this, a relation between the agreed power of the installation (S_i) and the short circuit power at the point of evaluation (S_{sc}) is used through (2).

$$\frac{S_i}{S_{sc}} \leq 0.2\% \tag{2}$$

The limit of 0.2 % is used assuming that the system is currently operating with a level of distortion sufficiently below the planning level, that the amplification due to resonance is not expected to exceed a factor of two, and that there is no risk of interference with system equipment caused by connection of the new installation [3].

To characterize the amount of distorting equipment within the installation, a weighted distorting power criteria can be assumed. The weighted distorting power is calculated using (3). The weighting factors *Wj* are shown in Table II [3].

$$S_{Dwi} = \sum_{j} S_{Dj} \cdot W_j \tag{3}$$

Where S_{Dj} is the power of each distorting equipment (j) in the installation (*i*).

Assuming a conservative criterion, the acceptance of a new installation may be determined by comparing the weighted distorting power with the short-circuit power at the point of evaluation, as shown in (4) [3].

$$\frac{S_{Dwi}}{S_{sc}} \leq 0.2\% \tag{4}$$

Table II - Weighting factors Wj for different types of harmonic producing equipments [3]

Typical Equipment Connected to LV, MV or HV	Typical Current THD	Weighting Factor (W_j)
Single phase power supply	80 % (high 3rd)	2.5
Semi-converter	High 2nd,3rd, 4th at partial loads	2.5
6-pulse converter, capacitive smoothing, no series inductance	80 %	2
6-pulse converter, capacitive smoothing with series inductance > 3%, or d.c. drive	40 %	1
6-pulse converter with large inductor for current smoothing	28 %	0.8
AC voltage regulator	Varies with firing angle	0.7
12-pulse converter	15 %	0.5

After this, no studies are needed to obtain the emission limits as the fault level at the connection point will typically be known by the network operator. Even for locations where there is not yet a grid nearby, estimating the fault level is relatively easy.

A certain profile for source impedance versus frequency should be assumed and this same profile will be assumed for all locations. The system harmonic impedances can be obtained by simulation for various system operating conditions. This impedance may be based on the short-circuit impedance or on the locus of the harmonic impedance. It is necessary to consider the range of variation of harmonic impedance, not only the maximum impedance values in order to identify possible resonance [3]. The presence of resonances could result in high harmonic voltage distortion at a certain location, despite the emission from the plant being below the limit.

6. Verification of Limits

Once the limits are set, they need to be verified one way or the other. Also for this, different methods are in use, each with their own advantages and disadvantages.

A. Verification of Model Used

The network operator may give detailed instructions on how the calculations should proceed. As long as those instructions are followed and the resulting estimated emission is below the limits, the wind power plant is allowed to connect. However, if excessive harmonic distortion is estimated during the simulation, further analysis and solutions to the problem are required. No verification is done after connection.

Preliminary simulations should be performed to identify expected harmonic levels and system response characteristics. These simulations should be performed for different system conditions to identify the conditions of potential concern. A complex model in order to accurately determine frequency response characteristics is needed. Accurate representations for transmission lines, cables, transformers, capacitor banks, loads, and machines are required. The potential impact of the WPP should be evaluated at this point [1].

The risk of high emission and high voltage distortion is with the network operator. But it is the network operator that sets the instructions. The instructions often are based on rather extreme operational states and other worst-case assumptions. The risk carried by the network operator is therefore typically not very big.

The advantage for the wind power plants operator is that no detailed knowledge is needed for performing harmonic studies. Also, there is no risk that the plant cannot be connected once the criteria are complied with. Furthermore, once the design is approved by the network operator, the latter takes over all risks for high harmonic distortion.

As for this approach computer simulations, measurements, detailed models and data are needed, the requirements are typically more strict than would be absolutely necessary.

B. Verification of Current and/or Voltage Distortion

The harmonic emission level is defined as the magnitude of the harmonic current/voltage vector at each harmonic frequency at the point of evaluation. The harmonic emission vector results in increased levels of harmonic distortion on the network and the emission level needs to be less than the emission limits defined in the standard [3].

According to IEC 61000-3-6 [3], the harmonic emission level can be defined as the vector U_{hi} considering the distortion before and after the installation under consideration. Fig. 1 represents the approach.

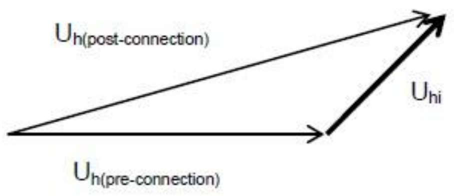

Fig. 1 Emission vector U_{hi} and its contribution to the measured harmonic vector at the point of evaluation [3]

In this approach the pre-connection assessment of the harmonic emission level for the WPP can be determined using basic assumptions about the characteristics of the system and its installations. However, as the actual emission level could be higher or lower than the calculated value. Therefore, it may be necessary to assess the level of emissions that will be present when the WPP is connected to the system [3].

The advantage for the network operator is that the harmonic distortion can be estimated with actual values and different operation situations. The disadvantage for the WPP owner is that there a risk that the plant cannot be connected when the limits are exceeded.

7. Voltage Distortion Limits

In this paper the voltage distortion limits related to IEEE 519 [2] and IEC 61000-3-6 [3] are presented.

A. IEEE 519 - Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

This recommended practice was prepared by a joint task force of the IEEE Power Engineering Society and the IEEE Industry Applications Society. It was published in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads [5]. A review was started in 1984, being published at 1992 incorporating the evolving understanding of the effect of static power converters and other nonlinear loads on electric power systems [1]. In the latest version (2014), the Point of Common Coupling is well defined, the Total Demand Distortion is redefined, a new statistical method of measuring and recording harmonic content is described, revised voltage distortion limits are established and the recommendations for increasing harmonic current limits put active and passive filters on an equal footing with phase shifted multipulse drives [6].

Regarding the voltage harmonic limits, at the point of connection, system owners or operators should limit line-to-neutral voltage harmonics as daily 99th percentile very short time (3 s) values and they should be less than 1.5 times the values given in Table III. Also weekly 95th percentile short time (10 min) values should be less than the values given in Table III [2].

Table III – IEEE 519:Voltage Distortion Limits [2]

Bus Voltage at Point of Connection	Individual Harmonic [%]	Total Harmonic Distortion THD [%]
$V \leq 1kV$	5	8
$1kV < V \leq 69$ kV	3	5
69 kV $< V \leq 161$ kV	1.5	2.5
161 kV $< V$	1	1.5

B. IEC 61000-3-6 Electromagnetic Compatibility (EMC) Part 3: Limits-Section 6: Assessment of emission limits for distorting loads in MV and HV power systems

The technical basis for IEC 61000-3-6 was originally developed by a joint CIGRE/CIRED working group in 1996 and provided guidelines for assessing the harmonic emissions from customers, rather than absolute limits that must be met. The primary objective was to provide guidance to system operators or owners for engineering practices [7]. In 2002, the CIGRE Study Committee C4 and CIRED Study Committee S2 organized an appropriate technical forum, whose main scope was to prepare, among other tasks, the revision of the technical report. Furthermore, WG C4.103 reviewed the procedure used to determine emission limits and the assessment methods used to evaluate emission levels for installations [3]. For the latest version, the following topics were reviewed: the point of evaluation and point of common coupling definitions, the definition of the harmonic emission level, the operating conditions to consider for evaluation of harmonic, emission limits, the indexes for assessing harmonic levels, the harmonic limits for short duration harmonics, resonance consideration, summation laws and the limits for inter harmonics components [7].

Considering the voltage distortion limits, the indicative levels are presented in Table IV.

Table IV - Indicative planning levels for harmonic voltages in MV, HV and EHV power systems

Odd Harmonics non-multiple of 3		
Harmonic order h	Harmonic Voltage [%]	
	MV	EV-EHV
5	5	2
7	4	2
11	3	1.5
13	2.5	1.5
$17 \leq h \leq 49$	$1.9 \cdot \frac{17}{h} - 0.2$	$1.2 \cdot \frac{17}{h}$
Odd Harmonics Multiple of 3		
Harmonic order h	Harmonic Voltage [%]	
	MV	EV-EHV

3	4	2
9	12	1
15	0.3	0.3
21	0.2	0.2
21 < h ≤ 45	0.2	0.2
Even Harmonics		
Harmonic order h	Harmonic Voltage [%]	
	MV	EV-EHV
2	1.8	1.4
4	1	0.8
6	0.5	0.4
8	0.5	0.4
10 ≤ h ≤ 50	$0.25 \cdot \frac{10}{h} + 0.22$	$0.19 \frac{10}{h} + 0.16$

8. Suitability of the Voltage Distortion Limits

The emission limits for wind power plants are in the end all based on what is considered as acceptable voltage distortion limits. There are two sets of such limits, both shown in Section 8. The limits used in IEC and Cenelec standards are all based on a 1981 paper presenting measurements at a range of locations in Europe [14]. The lower limits for higher frequency, for even harmonics and for triplen harmonics are simply a consequence of the lower levels of those harmonics present in European grids around 1980. Some minor changes have been made since then, including a slight rise in the permissible levels for the less common harmonic orders and a large rise for harmonic three. The latter occured most likely because of the large increase in single-phase distortion equipment. The origin of the IEEE standards is less clear, but they appear to originate from a UK standard that in turn assumed a simplified model for the harmonic distortion due to a large converter. The result is a flat spectrum, with identical limits for all odd harmonics. The limits for even harmonics have been set at one fourth of the limits for add harmonics. This factor four appears to be an arbitrary choice.

Emission from wind turbines is low at the harmonic orders that are normally a concern (low-order odd harmonics) but the emission is relatively high for even harmonics and interharmonics [15]. Concerns with connections are often for high-order even harmonics, where the justification for the limits is basically that these levels used to be low.

9. Conclusion

In this paper a discussion regarding the procedures and standards used to evaluate the connection of WPP into the public grid was performed. From this, it can be observed that depending on the used approach, different results and considerations took place. Voltage and current limits and assessment procedures can be used depending on the standard. Furthermore, depending on the point of view, (network operator and owner/operator of the WPP), a specific approach may be more advantageous for one part than to another. Furthermore, the modifications on the latest versions of IEEE 519-1992 and IEC 61000-3-6 were presented.

Different methods for setting emission limits and for verifying those limits have advantages and disadvantages for different stakeholders. There will not be any perfect method that is the best for any stakeholder. However the advantages and disadvantages of the different methods should be considered more transparently in the creating of new connection rules but also, and even more importantly, in the application of those rules. The rules are just a step in the requirement for the network operator to stay within planning levels and regulatory limits. This in turns is just one of the tools for ensuring a high probability of electromagnetic compatibility.

In the light of the latter, a serious reassessment of the different voltage distortion limits is needed. For wind power especially the high-order even harmonics seem to be a concern.

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