COMPARISONS OF IEC/TR 61000-3-6 AND IEEE STD 519 IN THE MV SYSTEM

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Abstract: The objective of this paper is to compare the harmonic allocation methodologies of both IEC 61000-3-6 [1] and IEEE Std. 519 [2]. Comparison has been carried in detail to analyze the weak and strong points of the conventional standards based on harmonic allocation.

Many engineers working for power quality (PQ) have been wondering which one they have to follow since both standards approach the issue of allocating the emission limits differently, and the solution set derived from both are not identical. On the surface, they are complement each other [3]. But an in-depth analysis has shown some significant differences [4].

It is impossible to compare directly both standards since they had been developed based on the different methodologies. Therefore, comparison has been performed with a key question that whether both solution sets ultimately arrive at the same conclusion or not. Authors desire to progress IEC 61000-3-6 and IEEE Std. 519 to complement each other towards smart standards that represent integrity and consistency in the future. It is necessary to integrate both standards

Keywords: Harmonic Standard, Harmonic Emission Limits, Distribution Automation, Power Quality

INTRODUCTION

With the increasing utilization of loads including electronics, which can be sources of harmonics and is sensitive to disturbances, the utility industry's concern for power quality continues to grow. The utility is responsible for the overall coordination of harmonic levels under normal operating conditions in accordance with national requirements. The customers are responsible for maintaining his own harmonic emissions at the point of evaluation (POE) [1] below the limits specified by the utility.

IEC 61000-3-6 and IEEE Std. 519 have by now been accepted as two well-known standards for interconnecting MV customers to utility systems and widely adopted standards to many power utilities. The ultimate goal of both standards is to limit actual harmonic voltages on a supply system to specific levels which will not result in adverse effects on equipment by limiting the emission limits to each customer so that they will not cause unacceptable voltage distortion levels for normal system characteristics.

Even though the goal is identical, the planning levels, the individual voltage and current emission limits allocated by both standards are significantly different. These differences have made utilities, which try to build their own standard, and engineers, who work for PQ, confused whenever their customers questioned the reasons of different solutions.

Until now, both standards have not been compared with analytical calculations because there is still no explanation that discusses the origin of emission limits in IEEE Std. 519, and the complex feature of IEC 61000-3-6.

IEEE Std. 519 can be considered as the simplest standard because the allowable emission limits are pre-calculated, but there is no rationale in its page. IEC 61000-3-6 unlike IEEE Std. 519 has clear rationales about all its own principles and has detailed formula for calculating the emission limits, but relies on the assumption for simplification; the assumption has defeated the excellent features of IEC 61000-3-6 since it leads the solution set to inaccuracy compared to the exact solution. A harmonic analysis program developed based on the deterministic and stochastic harmonic power flow method has been used throughout this paper.

No research, which has shown the problems of both standards with analytical proofs, has not been carried. Only limited studies have compared the differences of both standards [3] [4].

The objective of this paper is to compare the harmonic allocation methods and emission limits of both standards. The difference, inconsistency and inaccuracy problem have been proven with the perspective of practical evaluations based on their own principles. This paper will focus on the specific individual voltage and current emission limits in MV system.

OVERVIEW

The harmonic emission limits presented in IEC 61000-3-6 and IEEE Std. 519 standard have been accepted as a guideline of utilities for a long time. Comparing with long time acceptance, there have been only limited studies carried out about the emission limits of both standards. Theoretically, the harmonic standards should fulfill two ultimate requirements such as fairness and consistency.

Firstly, the planning levels in a given system should be shared fairly to each customer according to his or her size of contraction. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system.

Secondly, the harmonic standards should insure the systems not to be violated if all customers are in compliance with the standards. Therefore, when the system is fully loaded and all consumers are injecting up to their emission limits, the worst voltage distortion should be equal to the planning level theoretically in accordance with its own methodology.

In addition to these two requirements, it should have clear rationales about all its own principles for power utilities to adopt the standard with some modifications under the consideration of their own system conditions.

To justify these two fulfillments, the basic principles of both standards have been analyzed. Although many principles are in both standards, the voltage and current emission limits have been focused on in this paper. It is worthwhile to recall the developments of harmonic standards:

• Engineering Recommendation G5/3 (1976)
• CIGRE documents (early versions of the IEC standards): Voltage limits only.
• IEEE Std. 519-1982: Only harmonic voltage limits were specified in this standard.
• IEEE Std. 519-1992: Current emission limits were added. An example of several users on a single distribution feeder system was added
• IEC 61000-3-6 (1996): Current limits were added.
• Engineering Recommendation G5/4 (2001)
• IEC 61000-3-6 (2008): An example of application of the simplifying assumption was added.

IEC 61000-3-6

A large amount of space is dedicated to the description of the general approach of how to allocate the emission limits to all customers connected to a supply system on the basis of the probabilistic method.

The main procedure for allocation of the emission limits consists of three steps such as construction of a) Planning Levels, b) Individual Voltage Emission Limits and c) Individual Current Emission Limits. In each step, specific formulas are designed to insure two requirements. The formulas have considered the influence of all system uncertainties such as the network topology, stochastic nature of harmonics, the location of customer, the number of customers, agreed power, the power supply capability, the number of feeder and the system voltage level.

The formulas lead the emission limits to be more rigorously derived from the voltage planning levels. Authors completely agree with the philosophies of IEC 61000-3-6. Due to the wide consideration of the system conditions, IEC 61000-3-6 has been known as a complicated standard. It is so difficult to apply the emission limits to the practical system that engineers tend to avoid using this standard.

Actually, IEC 61000-3-6 has not provided the exact method to derive the solution set of the emission limits in accordance with its own principles. A simplified method has been proposed under the assumption of a uniform distribution of installations to avoid the complex calculation. Moreover, the method presented in the standard does not fully consider the network topology so that it is impossible to apply the allocation method to the complicated network topology such as the meshed and DG system.

The adoption of the simplified assumption might be due to the lack of tools for harmonic analysis based on the probabilistic concept several decades ago. However, the situation has changed significantly since then. We have justified that this simplification leads the solution set to significant inaccuracy. In other words, the standard fails to keep the second requirement a little.

IEEE Std. 519

Mr. Chris Duffey, who was group leader of IEEE Std. 519 limits, said that “The standard should stand by itself, on its own merits, with engineering proof within its pages to show that it has been properly thought out with measurable benefits to those who use its guidance” [5].

There is still no explanation that discusses the origin of the emission limits in its pages. This is contrast IEC 61000-3-6 that has clear descriptions of its own principles. Therefore, many power utilities have been wondered whether they can adopt this standard as their standard. Sometimes, without any study, this standard has been used without any consideration of a given system conditions. Without a careful study of the present emission limits, IEEE Std. 519 will be left as is without any analytical proof that they are correct. They will be accepted since they have always been.

Like IEC 61000-3-6, construction of a) Planning Levels, b) Individual Voltage Emission Limits and c) Individual Current Emission Limits are the main procedure for the harmonic emission allocation. However, all emission limits are pre-calculated with several categories instead of the specific formulas. As expected, the emission limits, which consist of several categories, have possibilities to fail the first requirement. It is easy to apply due to the pre-calculated emission limits. But it is difficult to believe the accuracy of the emission limits.

Moreover, the emission limits were designed without full consideration of the system conditions such as the power supply capability, the number of feeder and the system voltage level. Although the system condition varies, the emission limits are not changed. This fact leads the standard to fail to keep the second requirement.

For example, this is one reason why the standard should use the unfair “first come, first served” rule. To overcome this hurdle, account must be taken with the various power supply capability.

It is notable that the current emission limits have been originated based on the probabilistic concept. But the harmonic voltage evaluation method has been evaluated by the deterministic method. This leads the standard to be inconsistent to cause voltage violations theoretically. This standard fails to keep the both requirements as a harmonic standard. From now on, those problems have been clearly proven by comparison and justification.

COMPARISONS

We have presented the results of analysis in the perspective of practical applications through basic three steps such as a) Planning Levels, b) Individual Voltage Emission Limits and c) Individual Current Emission Limits.

Planning Levels

The current emission limits for individual equipment or a customer’s installation are developed based on the voltage emission limits. To allocate individual voltage emission limits of customer ‘i’ at harmonic order ‘h’ (referred to as ‘E_{Vhi}’ here), the planning levels should be determined first. The planning levels are specified by the utility for all voltage levels of the power systems. Actually, planning levels can be considered as internal quality objectives of the utility.

Therefore, the values of the planning levels give direct effects to the values of the individual voltage and current emission limits since the emission limits are derived by the planning levels. The planning levels are a stepping-stone for the harmonic allocation, and should be built based on good methodologies and reasonable philosophies.

Before beginning planning levels, the concept of the compatibility levels should be introduced. The objective of the compatibility levels is to limit actual harmonic voltages on supply systems to the specific levels.

Generally, planning levels are determined by equal to or lower than compatibility levels in order to give a safety margin to allow for data uncertainties and approximations used in harmonic allocation evaluation. Planning levels may differ from case to case, depending on system structures and circumstances. Some significant discrepancies of the planning levels between both standards have been found through the comparisons.

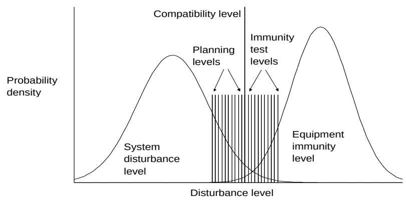
IEC 61000-3-6

The relationship between compatibility levels and planning levels is shown in Figure 1. Compatibility levels are defined based on the 95% probability levels of entire systems using distributions, which represent both time and space variations of disturbance. However, only indicative values of planning levels for harmonic voltages are shown in Table I since planning levels will differ from case to case.

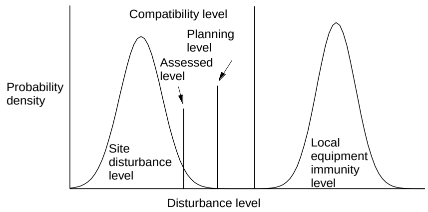
Table I. Compatibility levels for individual harmonic voltages in medium voltages networks [1]

Percent of fundamental component

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3	
Harmonic Order [h]	Harmonic Voltage [%]	Harmonic Order [h]	Harmonic Voltage [%]
5	6	3	5
7	5	9	1,5
11	3,5	15	0,4
13	3	21	0,3
$17 \leq h \leq 49$	$2{,}27 \cdot \frac{17}{h} - 0{,}27$	$21 < h \leq 45$	0,2
NOTE: The corresponding compatibility level for the total harmonic distortion is THD = 8%.			



a) Time/location statistics covering the whole system



b) Time statistics relevant to one site within the whole system

Figure 1. Illustration of basic voltage quality concepts [1]

IEEE Std. 519

Unlike IEC 61000-3-6, it is hard to find the concept of compatibility and planning levels in the standard. However, instead of planning levels, the concept of the voltage distortion limits are given according to the system voltage levels as shown in Table II. The limits are defined to minimize voltage THD to 5% in MV systems, and to have no individual harmonic above 3%. Sometimes it is called the five slant three criteria or 5/3. No explanation about where the 5/3 voltage THD criteria originated is in the standard. This might not be discussed in either the 1979 or the 1992 version of the standard [5].

For the purpose of comparison, we assume that the voltage distortion limits in IEEE Std. 519 are the same concept of the planning levels in IEC 61000-3-6. In this paper, we have used the voltage distortion limits as planning levels.

Table II. Voltage Distortion Limits [2]

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3%	5%
69.001kV through 161kV	4%	3%
161.001 kV and above	3%	3%

Note: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

From the comparison of planning levels in Table III, we can recognize that two standards have huge discrepancies from the beginning that cannot be ignored. As expected, these discrepancies cause the huge mismatches of the emission limits between both standards.

Who can think the solution set can be trustable and reasonable, if the solution sets were derived based on the planning levels having such a huge discrepancy. The first thing we have to do is to narrow down the gap of discrepancy in Table III, and to produce the rationale about the voltage distortion limits in the IEEE Std. 519.

Table III. Comparisons of planning levels in MV systems

Harmonic Order	IEC 61000-3-6	IEEE Std. 519	Discrepancy (%)
5	5%	3%	67%
7	4%	3%	33%
11	3%	3%	0%
13	2.5%	3%	17%
17	1.6%	3%	47%
19	1.2%	3%	60%
23	1.2%	3%	60%
25	1.2%	3%	60%
THD	6.5%	5%	30%

The results of the comparison for the planning levels has been summarized in Table IV.

Table IV. Comparisons of planning levels

	IEC 61000-3-6	IEEE Std. 519
Planning Levels	Detailed	Not Detailed
	Documented well	Not Documented well

Individual Voltage Emission Limits

After determining the planning levels, the next step is to set the voltage emission limits which shares the planning levels with all customers connected to the given system in proportion to their size of the agreed powers. In order to allocate the current emission limits of customer ‘i’ at harmonic order ‘h’ (referred to as ‘$E_{Ih,i}$’ here) to each customer, it is necessary to define the method to allocate $E_{Vh,i}$ to each customer.

The key concept of the allocation principles is the allocation of equal harmonic emission rights to MV customers in accordance with agreed power in a given system. It means that planning level in a given system should be shared fairly to each customer according to his or her size of contraction. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system. Some significant differences of the method to allocate $E_{Vh,i}$ have been shown.

IEC 61000-3-6

To evaluate $E_{Vh,i}$, the concept of the global contribution emission limits G_{hMV} is introduced at a given MV system. More detailed explanations of the G_{hMV} can be found in [1]. Instead of discussing the global contribution emission limits G_{hMV}, we assumed that G_{hMV} is the same concept of the planning levels in the MV systems.

Each customer who has only a fraction of the global contribution emission limits G_{hMV} will be allocated under the consideration of the considered aggregation of every harmonic source (probabilistic value). This approach is to take the ratio between the agreed power S_i and the total supply capability S_t of the given MV system.

$$E_{Vh,i} = G_{hMV} \cdot \sqrt[\alpha]{\frac{S_i}{(S_t - F_{ML} \cdot S_{LV})} \cdot \frac{1}{F_{MV}}} \quad (1)$$

where:

· $E_{Vh,i}$: Individual voltage emission limit of order h for the load (i) directly supplied at MV (%)

· G_{hMV} : Acceptable global contribution of the local loads directly supplied at MV to the h^{th} harmonic voltage in the MV system

· $S_i = P_i / \cos\varphi_i$: Agreed power of customer installation 'i'

· S_t : Total supply capacity of the considered system

· S_{LV} : Total power of the loads supplied directly at LV

· F_{ML} : Coincidence factor between the two distorting (aggregate) loads of the MV and LV distribution systems

· F_{MV} : Coincidence factor for MV loads distorting simultaneously

· α : Summation exponent

Equation (1) can be rewritten (2) if a simplified approach can be used under the condition of that all MV installations are considered to be in simultaneous use. More detailed explanations can be found in [1].

$$E_{Vh,i} = G_{hMV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \quad (2)$$

Equation (2) shows that $E_{Vh,i}$ is governed by the supply capacity S_t of the considered system (in this case, the HV-MV feeding transformer).

IEEE Std. 519

IEEE Std. 519 uses term "Maximum Individual Frequency Voltage Harmonic (%)" instead of term "Individual voltage emission limits". In the context of this paper, the concept of "Maximum Individual Frequency Voltage Harmonic" has been considered equal to the "Individual voltage emission limits" in IEC 61000-3-6.

From now, Maximum Individual Frequency Voltage Harmonic is referred to as $E_{Vh,i}$.

Additionally, IEC 61000-3-6 concept of "agreed power" is analogous to the maximum demand current in the IEEE Std. 519. The fixed set of $E_{Vh,i}$, which is directly proportional to short circuit ratio (SCR), has been provided in Table V instead of Equation (1) and (2) in IEC 61000-3-6. Table V shows that $E_{Vh,i}$ is not governed by the size of supply capacity unlike equation (1) and (2) in IEC 61000-3-6. The unit of the MV supply capacity follows the size of the HV-MV feeding transformer in a distribution substation. Table V obviously shows that $E_{Vh,i}$ is derived under the ratio of both the agreed power and short circuit power based on the combined effect of every harmonic source so that the sum of $E_{Vh,i}$ will not exceed the planning levels.

The serious problem caused by the fixed set of $E_{Vh,i}$ without any consideration of the supply capacity will be presented later. Moreover, like planning levels, no clear explanations are in the standard about Table V. The standard should have explained the origin of emission limits in Table V, and how the diversity factors are applied in Table V.

Table V. Individual Voltage Emission Limits [2]

SCR at PCC	Maximum Individual Frequency Voltage Harmonic (%)	Related Assumption
10	2.5-3.0%	Dedication system
20	2.0-2.5%	1-2 large customers
50	1.0-1.5%	A few relatively large customers
100	0.5-1.0%	5-20 medium size customers
1000	0.05-0.10%	Many small customers

The comparison of $E_{Vh,i}$ limits has been summarized in Table VI.

Table VI. Comparisons of individual voltage emission limits

	IEC 61000-3-6	IEEE Std. 519
Formula	Yes	No
Assumption	No	Yes
Diversity factor	Yes	Yes
Detailed Well	Yes	No
Agreed Power	Yes	Yes
Short Circuit Power	No1)	Yes
Supply Capacity	Yes	No
Rationale	Yes	No

1) Short circuit power at POE is considered in the step of the individual current emission limit.

Individual Current Emission Limits

The final step is to allocate the current emission limits $E_{Ih,i}$ to each customer so that utilities can assess compliance with a customer's installation based on $E_{Ih,i}$. The principles for allocating $E_{Ih,i}$ are discussed. Then, to compare both the solution sets of $E_{Ih,i}$, the case study for harmonic allocation has been carried out based on IEEE 123 distribution network model [6]. It will be rewarding study to investigate both solution sets. From the results of comparisons, the significant mismatches have been found between both standards.

IEC 61000-3-6

$E_{Ih,i}$ can be written

$$E_{Ih,i} = \frac{E_{Vh,i}}{Z_{hi}} \quad (3)$$

where Z_{hi} is the harmonic driving point impedance of the system at the point of evaluation assessed considering the actual purpose of converting voltage to current emission limits.

Some MV feeders have short circuit powers that vary by a factor 10:1 or more from the supply side to the far end. Equation (3) shows that the customers located at the far ends of feeders will receive a much lower allocation of the current emission limits compared to those located at the supply end. Alternatively, if the same current emission limits are allocated without the consideration of short circuit power, those connected to strong point will be given the current emission limits no greater than that given for weak connection points. It means that the power system harmonic absorption capacity is not fully utilized.

To alleviate between these two the impact of allocation policies, Set b), which has been shown in Table VII, is chosen as the treatment of customer impedances. Although Set b) is adopted here because it gives a good compromise between the emission allocation to each consumer and the system harmonic absorption capacity, the utility should choose the proper set under consideration of area characteristic such as urban, rural to maximize the system harmonic absorption capacity.

In Table VII, changing the assessment method from Set a) to Set b) to Set c) progressively increases the system harmonic absorption capacity but decreases the permitted emission at the far end of the feeder.

Table VII. Harmonic Current Assessment Method

Injection Method	Current constant	Power constant	Voltage constant
Injection Set Designation	A	b	c
I_h	K (constant)	$\frac{1}{\sqrt{Z_h}}$	$\frac{1}{Z_h}$

IEEE Std. 519

The individual current emission limit set has been shown in Table VIII. This is allocated in much less detailed than IEC 61000-3-6 since the solution set consists of only five categories. This means that it has possibility to happen an unfair allocation.

Table VIII. Individual Current Emission Limits[2]

Maximum Harmonic current distortion in Percent of I_L						
	Harmonic order (odd Harmonics)					
I_{sc}/I_L	<11	11≤h≤17	11≤h≤17	11≤h≤17	11≤h≤17	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

CONCLUSIONS

Through the comparison, the strong and weak points of the present standards have been properly proven based on analytical proofs and simulations. The comparison has been carried out on the basis of IEEE 123 network topology system. From the results of the comparison, the significant differences have been clearly shown such as the planning levels, individual voltage emission limits and individual current emission limits.

IEEE Std. 519 has failed to make the systems not to be violated when all customers are in compliance with the standards due to several factors. IEC 61000-3-6 has shown the inaccuracy in the solution set of the emission limits due to the simplifying assumption. Moreover, IEC 61000-3-6 cannot be applied to the practical distribution systems with large number of branches and buses. Finally, the single-line diagram of distribution system with four feeders has been proposed as an example system for distribution networks instead of the single-line diagram in the IEEE Std. 519.

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