HARMONIC STANDARDS - THE NEED FOR AN INTEGRATED PERSPECTIVE

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Abstract

Four conditions are necessary for the establishment of an effective harmonic standard. First, it must be comprehensive in that it adequately takes account of the complexity and dynamics of harmonic phenomena. Secondly, it must be flexible enough to accommodate varying conditions and different networks. Thirdly, it must be effective in guaranteeing the compliance with specified compatibility conditions necessary for proper operation of the system (equipment and loads). Finally, it must be simple, such that the operating engineer is able to understand and apply it whenever necessary. With these issues in mind, this paper presents a qualitative analysis of the existing standards for harmonic distortion by pointing to their limitations and their conflicting philosophical bases while emphasizing the need for an integrated approach that explicitly and comprehensively considers the complexity and dynamics of the harmonic problem. An overview of existing standards is followed by a description of fundamental/philosophical issues that need consideration and integration in the preparation of harmonic standards. Practical measurement problems and planning system considerations are raised and discussed. Some basic guidelines are presented.

1. Introduction

The drastic increase in the use of nonlinear equipment and loads for efficient voltage control and energy utilization has created a situation where harmonics are generated, injected, and propagated in every line and feeder in the system. As a consequence comprehensive, flexible, and realistic harmonic standards for an appropriate assessment and control of the state of the network concerning harmonic distortions has become a necessity rather than an academic exercise.

Since the United Kingdom Engineering Recommendation G5/2 of 1967 [1], many national and international standards dealing with harmonics from industrial type equipment have been prepared. Different standards have dealt in detail with different aspects of the problem. But none of them have dealt in a comprehensive way with what is required by the complexity of the situation involving the generation, propagation, interaction, dynamics, and the amplification of harmonics. Present standards are at best limited in scope and application and are at worst totally inadequate. Standards differ widely from country to country with respect to the numerical (deterministic and probabilistic) values of individual harmonics and total distortion, the locality of the application of harmonic limits, the electrical parameter (voltage or current), the time varying nature of the distortion and the consequent frequency characterization, the responsibility and action for correcting and enforcing the limits, etc. In addition the philosophical basis on system performance and economic considerations which shapes the various standards, are not explicitly stated in the documentation. The lack of technical evidence, necessary information, and data to back up assumptions, which are affected by personal and political forces, and blended by the complex democracy of technical committees, have created complicated, unrealistic, and ultimately conceptually erroneous standards. Consequently, the need for an integrated, less dogmatic, flexible, and realistic approach is imperative and urgently required. Several papers and documents [2 to 11] have dealt with this subject and have made numerous and excellent suggestions towards the establishment of a standard that might regulate a harmonious and controlled coexistence of harmonic producing and sensitive loads and equipment.

To summarize the salient issues, one can pose the following questions:

1. Is the harmonic phenomena, voltage or current, quasistatic or dynamic, fast dynamic or slow dynamic, deterministic or stochastic, and is statistical treatment of collected data needed or not?

2. Where are the harmonics to be measured near the offending nonlinear equipment, near the connecting network, or near the Susceptible Sensitive installation?

3. Which are the measurement procedure, measuring devices, assessment period, load and system conditions, etc?

4. What are the type of harmonics present (Modulated integral, subintegral, and superintegral)?

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2. Review of Previous Standards: What is wrong with them?

In the absence of an unanimous international recommendation concerning harmonic limitation, it is often asked what national recommendation is more appropriate to use. The appearance of new standards in the last 10 years show that the problem is becoming widely recognized, and an international agreement ought not to be too far away. For more information on standards and recommendations from Germany (DIN 57 160, Part 2), England (G. 5/3), Finland, France (D 648), Holland, Switzerland, Australia, New Zealand, Sweden, U.S.A. (Project IEEE 519) see references [12 to 23]. An observation which holds true for every standard considered is the dissociation from an integrated and evolving reality.

3. Philosophies - Approaches - Parameters

3.1 Limiting Parameters

The different ways to express the harmonic limits demonstrates the divergent approaches to address the problem. There are four basic parameters/approaches:

a) Harmonic Injected Currents

Some recommendations for example use the current which permits the establishment of absolute equality between clients. In general the permissible harmonic currents are proportional to the load size of each consumer and could be made dependent on the existing system harmonic pollution level for adjustment.

b) Harmonic Voltages I

The voltage takes into account the actual characteristics of the network harmonic impedance at the point of connection or anywhere in the network. This introduces some discrimination between clients, depending on system characteristics. Two variations occur:
- The limitation affects overall voltage harmonics, which means that the permissible added harmonics are a function of the pre-existing harmonic voltages.
- The limitation bears directly on harmonic voltages added, which means that all clients connected at the same point of the network are placed on an equality of footing, but that the "utilization" of the network remains partial. The issue of equality versus system maintainability level has to be resolved before setting any harmonic guidelines or standards.

c) Harmonic Voltages II

This approach takes account of the characteristics of the local network with a margin of security concerning the potential of local resonance phenomena. Two variances exist:
- First, the limitation is proportional to the maximum power of the user, while it is independent of system ambient levels and system impedance at resonance conditions.
- Second, values for the stipulated impedance take into account the actual resonance of the network and apparent system impedance. In summary, there exists a contrast and contradiction between system dependent limits versus equal or prorated harmonic allocations.

d) Hybrid (currents and voltages)

Other recommendations are hybrid, in the sense that currents and voltages are applied altogether. Since most solutions to harmonic distortion problems consist of changing the system frequency response and taking the dynamic and vectorial nature of the summation of the distortions from a multitude of sources the hybrid current/voltage parameter approach seems to take into account the complexity and evolving nature of the situation.

3.2 Flexibility

Flexibility in terms of application should be a desired characteristic of a good standard. The details, procedures, and flexibility of applications should be fully explored in the text of the recommendations.

3.3 Approaches

A pertinent comparison of the different recommendations is almost impossible. Different approaches are used. For example, some recommendations do not establish a direct connection between the harmonic limits permissible for a consumer and the system limits permissible in the network. It is supposed on the basis of a general hypothesis, that the respect of individual limits guarantees a small risk of exceeding the overall limits. Alternatively, other recommendations show their objectives clearly and define the individual limits in direct relation to system limits.

4. The Approach Desired: A Philosophical Consensus

Two basic points that require immediate action are the compilation of existing practices and knowledge, and suggestions for the philosophical basis of a consensus among all interested parties reflecting the fact that the various countries in the world have different geographical and economical situations and have a different philosophy on the subject, the limits of compatibility should be given in such a way that various cases could be treated using the same rule. Flexibility seems an important requirement. International Bodies, such as UIE, UNIFEDE, CIGRE, have Technical Committees and Working Groups engaged on the subject, with more emphasis on the technical side. More important for the moment than the discussion of actual limits, is the comparison of various philosophies of the approaches used in the different standards and recommendations. A list of basic parameters and issues that need precise definition and an integrated consideration are suggested later in this paper.

5. The IEEE Project 519

The IEEE 519 (Guide for Harmonic Control
and Reactive Compensation of Static Power Converters) [23] was developed to provide guidelines for applying static power converters in industrial plant environments. Voltage distortion limits and guidelines are proposed. The document is an excellent and comprehensive paper to inform the power industry community about technical aspects such as harmonic generation, system characteristics, effects, compensation, analysis methods, monitoring, and measurements of harmonic distortions. Considerable amount of space is devoted to the description of the topics mentioned above, while the final recommendations regarding the limits are presented in a succinct form, without comprehensive justification for the values used, and it also fails to clearly address important aspects related to the application of the established limits, such customer and utility responsibility, global and individual limits, pre-existing background distortion, evolution of the network, effect of the summation of multiple sources, etc. In addition, it has been reported that difficulties in meeting the recommended limits have been noted at the lower voltage range, because the multitude of harmonic sources have raised distortion levels [24].

6. The New CIGRE 36-05 Recommendation

The general philosophical trend proposed by CIGRE WG 36-05 [25] is the following:

- It is proposed that an approach which enables the problem of acceptance of loads with non-linear characteristics to be dealt with in stages, according to the size and type of equipment.

This general philosophy may be kept as it is, but the way in which the limits were expressed was appropriate to the case of MV systems and has yet to be adapted for HV and VHV ones.

Advanced assessment of harmonic voltages must be worst case but under normal system operating conditions (no outage but allowing for daily and seasonal production variations). The suggested multi tier acceptance process provides flexibility and allows future system conditions to reflect in future adjustments to allowable customer limits.

7. Fundamental / Philosophical Issues: The Need for An Integrated Approach

Following are a list of parameters and/or issues that require precise definitions, with an integrated perspective in mind, for the establishment of a comprehensive standard:

7.1. The Harmonic Distortion Phenomena: Is it to be treated as different or part of power quality issues?

Basic Time and Frequency Definitions / Differentiation:

- Frequency
- Magnitude (V,I)
- Waveform (V,I)
- Symmetry (V,I)

- Fast Dynamics
- Quasi-static
- Interharmonics and Subharmonics and Modulation type harmonics

7.2. Harmonic Distortion (Characterization):

- Generation
- Penetration / Summation and stochastic nature
- Interaction: Resonance
- Total Distortion Level or Individual Harmonics?
- Voltage or Current? or both?
- Harmonic Voltage at the Point of Common Coupling of a nearby substation or anywhere within an immediate area are a of influence?
- Global and Individual Values for system or customer or both?
- Short Term or Long Term Quasistatic Harmonic Exposure or Particular Wave-Shape?

8. The Interrelation Utility vs Customer

The choice between harmonic current and harmonic voltage limits is actually a choice between two approaches to the equality of rights for consumers and responsibility between the customer and the utility. Some comments are as follows:

- The harmonic current limit provide each consumer, large or small, with equal rights.
- The limit should be given as a percentage of the average fundamental current so that large and small consumers are treated equally.
- Harmonic voltage limits should be specified to avoid the utility to be solely responsible for correcting local parallel resonance problems.
- Individual and total harmonic voltages are required to assure a stable control of the situation as the network evolves. Such system voltage limits could have a toleration band depending on area or pre-installed ambient levels.

Among other aspects to be considered are:

- The Social, Political and Economical parameters vs. Limits
- The Continuous Evolution of the Situation and possible future problems necessitating limit readjustment for new customers.
- Time or Frequency Domain Studies and technique used in measurement, test equipment and statistical treatment.

9. Harmonic Asymmetry: Limitation and Prediction

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Extremely high unbalances have been observed by simulation \([26,27]\) and measurements, indicating that the assessment and limitation of the harmonic distortions of a network using a balanced phase approach, as traditionally done, should take into account the natural asymmetry of the network at harmonic frequencies.

While transmission and distribution systems can be modeled with certain accuracy by a single phase positive sequence (equivalent PI model for transmission lines) representation in harmonic studies, it is necessary to expand to a three-phase representation when a more accurate assessment of the harmonic impedance of the network is desired. The ground impedance modelling and how it reflects on the transmission line harmonic model is also an issue.

Coupled and non-homogenous elements such as mutually coupled transmission lines with different tower geometries and transpositions over the line length, and highly unbalanced loads are possible in a practical system. This is particularly important under unbalanced operation, a condition which is most likely to happen.

Therefore, three phase unbalanced programs for the assessment of the impedance of a network could be very helpful when a detailed phase state of the system is required. It will prove to be particularly helpful provided that accurate data and network component models are used.

The reluctance to use three phase representation is based on the enormous amount of data and computation time necessary. This limitation becomes less restrictive as the memory and speed of computers improve.

The three phase representation seems particularly important in ripple-control penetration studies, interference problems, and accurate determination of resonant points for filtering performance studies.

10. Multiple Sources: Summation and Probabilistic Characteristics

One aspect of assessing the harmonics tolerated by a power system is the estimation of the sum of harmonics arising from the various sources. The assessment of harmonics is not exact or uniform, since there will be unpredictable variations in either the non-linear sources and/or parameters of the system which affect the summation.

The combination of a number of harmonic sources will generally lead to less than the arithmetic sum of the maximum values due to uncertainty of magnitude and phase angle. Hence the resulting summation is extremely difficult to estimate accurately. In many practical cases, there is sufficient diversity in phase angle to make a worst case analysis based on the algebraic sum of the harmonic magnitudes extremely pessimistic. Standards based on this worst case approach therefore run the risk of causing unnecessary expense.

11. Real Life Situation: Integrate or Disintegrate?

The harmonic distortion caused by each separate distorting load or equipment in the supply system may not be assessed by the individual characterization of each source. A time varying vectorial summation is the precise way for such determination. Theoretically speaking, the characterization of the magnitude of the harmonic currents injected into the network as the main parameter to limit the connection of a distorting load does seem to downplay the physical mechanism of the combination of harmonics sources. On the other hand, the precise assessment of the contribution of each distorting load, considering the magnitude and phase angle of each harmonic component would lead to unacceptable computation complications. In such cases, it might be argued that each source be required and provide his own corrective means, i.e. harmonic filters, but this could lead to catastrophic results. Alternatively harmonic generating loads would not be a problem if the supply system would present an extremely low harmonic impedance at the connection point. Who is who as far as responsibility to correct the problem is concerned? How can we apply the limits to such a disorderly situation?

The complexity and dynamics of such environment requires standards to be flexible, particularly for the customers already connected to the network, and to have an approach that integrates and balances the physical nature of the problem and practical aspects of enforcing the acceptable limits. This is a point that requires wide acceptance if we are to make any progress.

11.1 Performance and Measurement Techniques

Compliance with harmonic guidelines or standards requires a readily and noncontroversial measurement of the harmonic levels. There are a number of issues in this area which a standard needs to address. These include:

a. Location of the measurement. Harmonic levels are readily measured at some locations, while at others can be taken only with difficulty and expense. Harmonic voltage levels at secondary distribution voltages can generally be measured directly on or with installed voltage transformers. Currents can be measured with simple clamp-on current transformers or Hall effect devices. Harmonic voltages at the metering point can often be measured through the installed voltage and current transformers. Measurements at primary distribution voltages are more difficult, and generally require the temporary installation of current and voltage transformers/transducers. While this equipment is available, the expense of these measurements is greater than that associated with using installed devices. Measurements on the transmission system generally are limited to installed current and voltage transducers. While the current transformer can generally be relied upon, voltage transformers and transducers can be subject to internal resonances and are also sensitive to nonlinear loads. Care should be taken to assess the frequency response of these devices prior to relying on measurements.
of their output.

b. Length of measurement. In many cases, the maximum harmonic level will not be present at the initial measurement. It can be expected that levels will fluctuate to some extent with system loading and voltage level. It has been observed that the highest harmonic levels often occur during light loads, so that overnight and weekend measurements are needed to show compliance with harmonic voltage limits.

c. System state. Changes in the power supply system cause changes in the harmonic impedance and therefore the harmonic voltage levels. In particular, the switching of power factor correction capacitors on the distribution system can cause large changes in harmonic voltage levels. When investigating a harmonic voltage level complaint, it is necessary to check the system in the configuration which led to the complaint.

d. Locating harmonic sources from measurements. While conceptually this would appear to be feasible, it is often difficult. A method involving a number of simultaneous measurements has been reported. Radial system methods based on the direction of real power flow often fall due to the combination of highly reactive power flow at the harmonics and phase angle error in the measurements. On the distribution system, it is often easier to examine the load and look at new installations of suspect devices rather than to trace a harmonic load through measurements.

e. Measurement equipment. A wide range of equipment is available for performing the measurement. This equipment is largely digital based, and generally depends on and FFT algorithm for determining the harmonic levels. Both synchronous and asynchronous sampling are available. The primary criteria in performing the measurement is to avoid measuring transients and the nonharmonic frequencies which are occasionally present. An oscilloscope can be used to study the waveform for stability. Nevertheless, measurement of a single cycle should not be used to determine harmonic levels. Some type of averaging, often built into the instrument, should be employed, and the operator should verify that these levels are stable. Good measurement practice is required to avoid spurious measurements due to coupling and grounding problems.

In the somewhat unusual case where harmonic levels are subject to fluctuation in the second to minute time range, this must be noted and dealt with accordingly. These fluctuations will most often be due to a single large load.

A standard which takes these issues into account and sets forth a clear and unambiguous method for determining harmonic levels will greatly ease the acceptance of the standard and subsequent discussions on compliance.

12. Responsibilities: Who Pays the Bill?

This is a legal issue which should be left out of this paper, but the fact that system and load interaction cannot be avoided make it logical to put the blame on both parties.

The goal of the standard should be to achieve an equitable distribution of the cost of compliance. While a large share of responsibility undeniably rests with those creating harmonics, there remains the responsibility of the power supply system to have a reasonable response to the harmonic excitation. Furthermore, sensitive loads must exhibit a certain minimum immunity to the harmonic levels. Great care must be taken in setting standards to attain the proper relationships between these three entities.

13. What About Low Voltage Harmonic Sources
(Background Distortion)

TV receivers are a main source of harmonics at the low utilization voltage. Significant measurements of distortion produced at low and higher voltages have been made [28,29]. This suggests a different approach to specifying allowable harmonic levels per voltage class, while acknowledging the role of ambient harmonics.

Ambient harmonics may have to play a more prominent role when allocating the right share of harmonic limits to the future large industrial consumers.

14. Planning System Considerations

(a) Harmonic Penetration Studies - How Accurate are They? Single-phase or Three-phase studies?

Considering that the power system is composed of many meshed parts and interconnected components with variable conditions, the benefit of the three-phase representation is dependent on the extent and nature of the problem being investigated, and on the accuracy of all parameters involved in the system representation (see section 9).

(b) Expansion of the Network vs Evolution of the Distorting Loads:

Limits should always incorporate the possibility of future deterioration in harmonic distortion and acceptable state of the system. For example a certain offset/overhead (of an acceptable maximum harmonic distortion per customer already considering the possibility of multiple disturbing loads) value could be incorporated to the individual and global harmonic limits in order to take into account facts such as unexpected disturbing loads, abnormal harmonic generating conditions, resonances, uncertainty of data / results concerning harmonic predictions, and natural but unexpected aggravation of local series and parallel resonances caused by the continuous and dynamic harmonic system impedance behavior.

With such approach to the establishment of harmonic limits the utilities could buy crucial time to try to keep the distortion
under acceptable absolute values. The offset/overhead value suggested would not have to be very high since the vectorial nature of the harmonic composition (which is on our side) reduces the probability of an arithmetic composition of the contribution of the several possible sources.

15. Criteria for Harmonic Standards

Following are the basic parameters that need to be considered well-defined for the establishment of effective harmonic standards:

- Frequency deviation.
- Voltage peak values.
- Overvoltage/overcurrent conditions.
- Harmonic voltage/current content in waveforms.
- Probabilistic nature of multiple adjacent harmonic sources.
- Adequate instrumentation and long-term data collection systems.
- Distinction between different network voltage classes, i.e., Transmission, sub-transmission, distribution, utilization.
- Classification of the generated harmonics as either quasi-steady state or transient in nature.
- Limitations on levels of current harmonics injected into the supply utility system in order to ensure less voltage distortion and block any possible harmonic penetration pattern that is usually the culprit in most harmonic noise interference problems.
- Definition of individual harmonic levels based on previous knowledge of possible excessive disturbing influence and use of total harmonic current distortion as a measure of their aggregate effect.
- Instrumentations to allow monitoring and analysis of stochastic nature of harmonic production, penetration, and their effects and need for statistical data treatment before assessing or enforcing any limits.
- Planning/expansion considerations to account for the evolution of the network state regarding harmonic distortions.

16. Final Observations - Some Guidelines

An electric utility should ensure that the power quality of the supply system is adequate at all places, and those customers using nonlinear type loads should be prepared to assume some responsibility in correcting any potential and alarming distortion problems.

A comprehensive standard for harmonic distortions should be flexible based on the following factors:

- Limitations on voltage waveform distortion level at any point of an immediate area of influence. (Both THD, Individual harmonic limits).
- Limitations on current distortion level at customer interface bus (Both THD, Individual harmonic limits, percentage of the average fundamental current).
- Limitations on I.T. and possibly KV.T levels as indication of potential noise interference at any point of an immediate area of influence. (Both I.T Residual and KV.T balanced).

Different levels of harmonic standards are to be specified according to the voltage class of the network with a three tier toleration band to allow harmonic level future adjustments:

- Transmission
- Subtransmission
- Distribution
- Utilization voltage high low

The limits chosen should reflect the compromise between the existing/background levels as well as maximum level of tolerated waveform distortion.

A distinction should be introduced between quasi-steady state and dynamic fast transient-type harmonics.

Individual and global limits should be established.

The evolution of the interaction between the system and the increasing number of non-linear loads and equipment should be taken into account by incorporating an offset/overhead component for the individual value assigned to each customer.

Periodic system harmonic measurements and harmonic survey of the utility network would serve as the basis for the establishment of the limits for given system-area.

17. Conclusions

The paper presented a qualitative review of harmonic limits, guidelines, and standards and the difficult task of compromising system tolerable limits with customer equitable allocations. The basic issues are recognizing the harmonic phenomena, quantifying the testing procedure with an eye on the future, and demanding continuous evolution and adjustment or review of a tolerable acceptable band of limits. The allocation of harmonic limits per voltage class is a valid approach. Both system voltage and customer injection limits should be specified. Other indices such a I.T. and noise levels are necessary when dealing with noise interference potential.

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