RECOMMENDED METHODS OF DETERMINING POWER QUALITY EMISSION LIMITS FOR INSTALLATIONS CONNECTED TO EHV, HV, MV AND LV POWER SYSTEMS

Germain BEAULIEU
Hydro Quebec – Canada
beaulieu.germain@hydro.qc.ca

Robert KOCH
Eskom – South Africa
robert.koch@eskom.co.za

Mark HALPIN
Auburn University
halpin@eng.auburn.edu

Luc BERTHET
EDF – France
luc.berthet@edf.fr

Paper presented on behalf of CIGRE/CIRED JWG C4.103[1]

ABSTRACT

An overview of the work accomplished by the joint working group CIGRÉ/CIRED C4.103 entitled "Emission Limits for Disturbing Installations" is given in this paper. This work included the delivery to IEC of three technical reports concerning emission limits for harmonics, flicker and voltage unbalance for installations connected at medium, high and extra high voltages, and a fourth report that will cover emission limits for low voltage installations.

INTRODUCTION

Joint working group CIGRE/CIRED C4.103 (Emission Limits for Disturbing Installations) was formed in late 2003 with the scope of preparing four technical reports deliverable to the International Electrotechnical Commission (IEC) for updating, simplifying, and supplementing international recommendations on how to set and apply emission limits for the connection of disturbing installations [1], [2]. Some 32 experts from 19 countries were appointed to the working group (WG) to prepare four technical reports. The objective of these reports is to provide guidance to system operators or owners on engineering practices related to emission levels that facilitate the provision of adequate service quality for all connected customers. The reports address the allocation of the capacity of the system to absorb disturbances. The aim is to coordinate the disturbance levels between different voltage levels in order to meet the compatibility levels at the points of utilization of electricity across the system.

BASIC EMC CONCEPTS

Emission limits for individual equipment or a customer's installation should be developed based on the effect that these emissions will have on the quality of the voltage. The following concepts are used to coordinate the emission of disturbances with the voltage quality objectives.

Compatibility levels

Compatibility levels are reference values for coordinating the emission and immunity of equipment or installations which are part of, or supplied by, a supply system in order to ensure the EMC in the whole system. These are generally based on the 95 % probability levels of entire systems, using distributions which represent both time and space variations of disturbances. The compatibility levels for disturbances in public LV and MV power systems are given in the standards IEC 61000-2-2 and IEC 61000-2-12.

Planning levels

Planning levels may be considered as "internal" quality objectives of the system, and should facilitate the co-ordination of disturbance levels between different voltage levels. They are equal to or lower than compatibility levels. Planning levels may differ from case to case, depending on system structure and circumstances. Indicative values for harmonics, voltage unbalance, flicker and rapid voltage changes at MV and HV-EHV are given in the reports. They are based on compatibility levels at MV and on existing HV-EHV practices, and consider the need to provide margin between LV, MV and HV-EHV for the purposes of overall EMC coordination. The reports also provide guidance for adapting or sharing planning levels between different parts of a system.

Methods and indices for assessing measured data against the planning levels are recommended. The recommended indices are characterized by their time integration interval (e.g. short term flicker level assessed over 10-minutes intervals) and a statistical value – percentile value over the observation period – to be used for comparison against the planning level (e.g. the 99% daily or 95% weekly values).

---

[1] Cigré/Cired Joint Working Group C4.103 consists of : G. Beaulieu (Convenor), P. Goossens (secretary), R. Koch, M. Halpin, L. Berthet, A. Baitch, M. McGranaghan, M. Lahtinen, J. Sinclair, J. Schonek, V. Gosbell, G. Bartak, H. Rochereau, M. Bollen, G. Borloo, H. Bronzeado, M.B.S. Diaz, G. OhEidhin, Z. Emin, S. Georghe, O. Gonbeau, U. Grape, Y. Hirata, J.L. G-Iglesias, K. Heidenreich, L. Fickert, P. Maigler, S. Malgarotti, C. Namhun, C. Unger, G. Valtorta, A. Zobaa.

For measurements, the reports recommend use of class A methods defined in IEC 61000-4-30.

Emission levels

The emission level from an installation into the power system is defined as the magnitude of the disturbing voltage (or current) vector which the considered installation gives rise to at the point of evaluation. This is illustrated by the vector U_{di} in Figure 1.

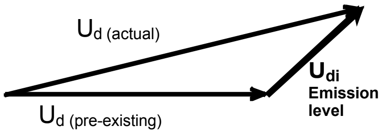

Figure 1: Illustration of the emission vector U_{di} and its impact, together with the pre-existing level at the point of evaluation, on the actual level of disturbance.

Where the emission vector results in increased levels of disturbance on the network (i.e. $|U_{d(actual)}| > |U_{d(pre\text{-}existing)}|$), the emission level (i.e. $|U_{di}|$) is required to be less than the associated emission limit.

The recommended co-ordination approach relies on individual emission limits being derived from the planning levels. For this reason, it is recommended that the same indices be applied when assessing emission levels (i.e. $|U_{di}|$) against the corresponding emission limits, and when assessing the actual (measured) voltages (i.e. $|U_{d(actual)}|$) against the planning levels.

The above definition takes into consideration that various types of interaction between the supply system and the installation may result in an increase or a reduction of the disturbance level on the system (e.g. in the case of harmonics, amplification of upstream harmonic voltages as a result of a resonance condition caused by a customer's shunt capacitors). As these documents address the EMC co-ordination requirements, such phenomena need to be taken into consideration in the assessment of actual emission levels.

GENERAL PRINCIPLES

The objective is to limit the total disturbance caused by all disturbing installations to levels that will not result in voltage disturbance levels that exceed the planning levels. Three steps are given in order to assign individual customer emission limits in a consistent and comprehensive manner:

i) adoption of a general summation law for accumulating disturbances arising from various sources;

ii) allocation of global contributions at a given voltage level to ensure co-ordination between different parts or voltage levels of a system;

iii) assignment of emission limits to disturbing installations based on the sharing of the global contributions.

Summation of numerous sources of disturbances

The global level of disturbances due to randomly disturbing installations is the result of the vector summation of each individual source of disturbance. The following general summation law can be adopted on the basis of experience:

$$D = \sqrt[\alpha]{\sum_i D_i^{\alpha}} \qquad (1)$$

where:

- D is the magnitude of the resulting disturbance level after the aggregation of various sources;
- D_i is the magnitude of the disturbance level produced by one of the various sources of disturbance to be combined;
- α is an exponent depending mainly upon the type of disturbance, the chosen value of the probability for the actual value not to exceed the calculated value and the degree to which individual disturbances vary randomly in magnitude and phase.

Indicatives values for the summation law exponent (α) are shown below, noting that other values may be used when more specific information is available – important particularly where the disturbances are not random in time.

Table 1 - Indicative values for exponent α.

Harmonics			**Flicker**	**Voltage unbalance** (negative sequence)
h <5	5 ≤ h ≤10	h >10		
1	1,4	2	3	1,4

Sharing global contributions between voltage levels

The principles recommended for determining the global disturbance contributions in a MV substation are illustrated below. In Figure 2, the level of disturbance at MV is the sum of the emissions from all installations and equipment connected at LV, MV and HV or upstream system.

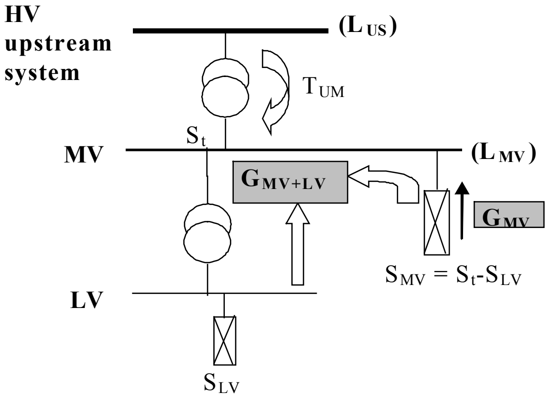

Figure 2: Example of a system for sharing global contributions at MV (see the definitions below)

Once the planning levels are set, the global contribution to the relevant voltage disturbances (harmonics, unbalance, or flicker) that can be allocated to all MV and LV installations supplied from the considered system is given by:

$$G_{MV+LV} = \sqrt[\alpha]{L_{MV}^{\alpha} - \left(T_{UM} \cdot L_{US}\right)^{\alpha}} \qquad (2)$$

where:

- G_{MV+LV} is the acceptable global contribution of the local MV and LV installations (S_{MV} and S_{LV}) to the voltage disturbance in the MV system when the total capacity of the MV system (S_t) is utilised;
- L_{US} is the planning level for the upstream system (different planning levels may be needed for intermediate voltage levels between MV and HV-EHV; this is why the general term of upstream system planning level is used);
- T_{UM} is the transfer coefficient of the disturbance levels from the upstream system to the MV system under consideration (determined by simulation or measurements);
- L_{MV} is the planning level for the considered MV system;
- α is the summation law exponent.

For an initial simplified evaluation, the transfer coefficient from the upstream system to a MV system can be taken as equal to 1. In practice however, the transfer coefficient may, in the case of harmonics, be larger than 1 due to harmonic resonance conditions. In the case of flicker and unbalance, the presence of three-phase machines on the MV and LV systems may result in a transfer coefficient of significantly less than 1. It is the responsibility of the system operator or owner to determine the relevant values.

Allocation of individual emission limits

The following methods relate to the so-called stage 2 procedure which normally applies to large installations. Stage 1 allows a simplified evaluation for small installations, and stage 3 allows more emissions on a conditional basis. In the recommendations of the WG, installations may be loads or generators.

HARMONICS

In order to leave room for every installation's emissions, only a portion of the global contribution to disturbances G_{hMV+LV} can be allocated to any individual disturbing installation connected to the considered MV system. A reasonable approach is to apply a proportional allocation based on the ratio between the agreed power S_i of the installation under consideration and the total supply capability S_t of the system. Such a criterion is justified based on the fact that the agreed power of an installation is often linked with that customer's share in the investment costs of the power system.

$$E_{Uhi} = G_{hMV+LV} \sqrt[\alpha]{\frac{S_i}{S_t}} \qquad (3)$$

where:

- E_{Uhi} is the harmonic voltage emission limit of order h for the installation (i) directly supplied at MV (%);
- G_{hMV+LV} is the acceptable global contribution of the local MV and LV installations to the h-th harmonic voltage in the MV system, as given by equation (2);
- $S_i = P_i / \cos\varphi_i$ is the agreed power of customer installation i, or the MVA rating of the considered installation (either load or generation);
- S_t is the total supply capacity of the considered system including provision for future load growth (S_t might also include the contribution from dispersed generation, however more detailed consideration will be required to determine its firm contribution to S_t and its effective contribution to the short-circuit level as well);
- α is the summation law exponent and is dependent on h.

Emission limits can also be converted from voltage to current using a specified impedance at each frequency.

A similar but more advanced approach is recommended at HV-EHV. However, the common HV-EHV harmonic planning levels between different parts of a system must first be shared, in particular in meshed systems. A method is recommended in the report that assesses the harmonic influence coefficients between various points in the system, taking into consideration resonance conditions that can cause higher distortion at other buses remote to the point of evaluation.

UNBALANCE

A similar approach to that used for harmonics has been recommended for developing unbalance emission limits. As power systems are not generally perfectly symmetrical, it is necessary to make a provision for the system's inherent sources of voltage unbalance (e.g. line impedance asymmetries). A factor k_{uE} is introduced to account for the portion of the allowed global unbalance level that can be allocated to unbalanced installations. The emission limit for an installation to be connected to a MV system is therefore:

$$E_{u\,i} = \sqrt[\alpha]{k_{uE}} \quad G_{uMV+LV} \sqrt[\alpha]{\frac{S_i}{S_t}} \qquad (4)$$

where:

- $E_{u\,i}$ is the voltage unbalance emission limit of the installation (i) directly supplied at MV (%);
- k_{uE} is the fraction of the global contribution to voltage unbalance that can be allocated for emissions from unbalanced installations in the considered system (guidelines for the selection of an appropriate value for k_{uE} are given in the report);
- G_{uMV+LV} is the acceptable global contribution to the voltage unbalance in the MV system of the MV system inherent asymmetries and of the unbalanced installations supplied at MV and LV.

A further consideration is that unbalance caused by three-phase customer installations may not necessarily be random in time, but may be assumed for the purpose of allocating emission limits to be randomly connected to the three phases of the system. Active selection of phase connections is intended to be applied in the case where unbalance is known in order to manage unbalance on such networks. It should also be noted that the report does not address the allocation of "unbalance emission limits" to single phase installations, as the physical connection to the network should be managed by the system operator or owner.

FLICKER

A similar approach as for harmonics and unbalance is recommended for flicker. Flicker attenuation from upstream to downstream systems is also important to consider - especially in the case of large installations such as arc furnaces connected at HV-EHV.

The presence of rotating machines at lower voltage levels downstream from a higher-voltage supply system may significantly attenuate flicker. It is reasonable to expect an attenuation coefficient of 0,8 between HV-EHV and MV whereas the attenuation from MV to LV is much less pronounced. Typical MV to LV attenuation coefficients may be taken as 1,0 due to the lack of significant large motor load at LV. The report on flicker gives indications on how to assess transfer factors.

In the case of flicker, it can be difficult to conduct pre-connection assessments of fluctuating installations. Similarly, it can also be difficult to practically assess post-connection contributions of particular installations to global flicker levels. Pre-connection assessment approaches of flicker levels for arc furnaces and other types of loads are also given in expanded annexes based on two main approaches. For relatively simple cases, techniques based on pre-determined shape factors are given for installations characterized by either periodic or non-periodic fluctuations. For more complex cases, simulation procedures are presented that can incorporate load currents and supply-system (background) flicker.

For rapid voltage changes, different IEC documents deal with this topic, but some inconsistencies still exist. A general review of the problems associated with rapid voltage changes would be needed to correlate the causes and effects so as to determine eventually the most appropriate assessment method. In the meantime, it is recommended that the assessment procedure be based on measured changes in r.m.s. voltage considering only the power frequency component with transients removed. In practice, the shortest possible multi-cycle window should be used to avoid artificially smoothing the desired r.m.s fundamental frequency voltage change. It should be remembered however that the levels or limits recommended for rapid voltage changes in the past were implicitly associated with the measurement methods in use at the time. In particular, previous recommendations were based on the magnitude of voltage change from the lowest point reached to the final steady-state value. This definition was found to be inconsistent both with what voltage fluctuation might actually be observed (via lighting) by end users and with what voltage fluctuation was often calculated for assessment purposes (e.g., motor starting voltage dip). To resolve these difficulties, the present recommendations are based on the voltage change from the pre-event steady state value to the lowest value reached during the event. See the definition of ΔU in Figure 3.

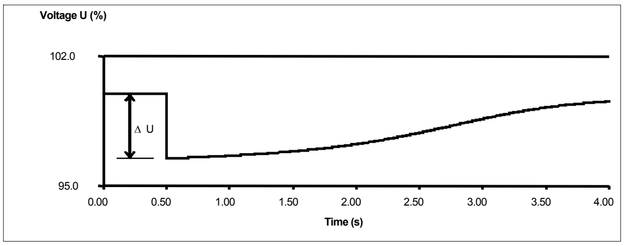

Figure 3: Example of rapid voltage change (motor start)

Because rapid voltage change limits are inherently designed to consider the situations that are outside the 10-minute window of any Pst value, statistical summation, via the summation law, of the effects of multiple rapid voltage changes is not appropriate. For this reason, no summation exponent is given. It is left to the system operator or owner to consider all rapid voltage changes that may occur over any particular time period and to insure that the cumulative effects do not exceed the recommended planning levels.

LV SYSTEMS

The fourth deliverable to the IEC only applies to large LV installations exceeding a minimum size. It is not intended to apply to residential installations, so the minimum size should be specified accordingly by the system operator or owner depending on their system characteristics.

Particular context at LV

For small installations, such as residential houses, generally the system operator or owner can rely on emission limits for individual pieces of equipment to meet the planning levels. For instance, IEC 61000-3-2 and 61000-3-12 in the case of harmonics, and IEC 61000-3-3 and 61000-3-11 in the case of voltage fluctuations are product family standards that define emission limits for equipment connected to LV systems.

As for the other reports, emission limits for LV installations are developed based on the effect that these emissions will have on the quality of the voltage. Consequently, the total of emissions from all sources contributing to the disturbances on the LV system should not exceed the planning level.

In order to define emission limits for large LV installations, it is necessary to consider that a number of other small installations subjected only to product standards as noted above may also contribute to disturbances on the LV systems.

So the method needs to be adapted to LV in order to take into account emissions from individual pieces of equipment, which are based on principles and assumptions different from those used for MV installations, and the fact that the percentages (in terms of power level or rating) of small and large installations are generally not known in advance and actually depend highly on the LV system considered.

Adaptation of the general principles

The recommended procedure is to set emission limits for large LV installations as follows.

- The allowable global contribution to disturbances in a given LV system is derived from the planning levels as recommended previously:

$$G_{LV} = \sqrt[\alpha]{L_{LV}^{\alpha} - \left(T_{ML} \cdot L_{MV}\right)^{\alpha}} \qquad (5)$$

- The emission limits for an LV installation larger than the specified minimum size are defined so that this large installation can replace a group of small installations of equivalent total power, which only comply with equipment emission limits, without increasing the global disturbance levels.

Application to harmonics

To further illustrate the method at LV, let us consider the case of harmonic disturbances. Figure 4 gives a typical LV system with a MV/LV transformer supplying n feeders through an LV busbar. The goal is to define the harmonic emission limits for customer installation (i) connected to feeder 1.

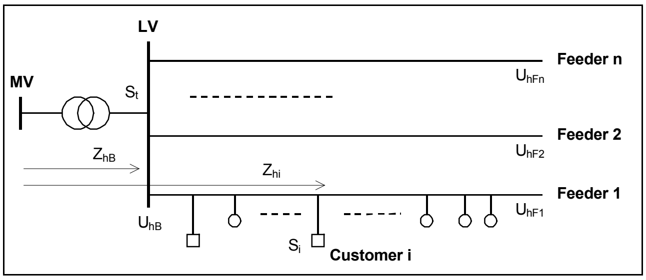

Figure 4: Typical LV system considered

It can be noticed that installation (i) only affects other feeders through the harmonic voltage it causes at the LV busbar.

Thus, both general following conditions have to be satisfied:

- The global contribution of all the LV disturbing installations assumed to be maximum at the far end of feeder shall not exceed the acceptable global contribution on LV systems G_{hLV};
- The global contribution of all the LV disturbing installations at the LV busbar level shall not exceed a portion G_{hB} of G_{hLV} as given by equation (6):

$$G_{hB} = K_{hB} \cdot G_{hLV} \qquad (6)$$

where K_{hB} is the ratio between both global contributions of the local LV installations, the one at the LV busbar and the other at the end of LV feeders, when the LV system is fully loaded by small installations.

The ratio K_{hB} depends only on the structure of the LV system (number and length of the feeders, distribution of customers, etc), the harmonic order h and the exponent α used for the summation law. Typical values and a method for estimating K_{hB} based on the actual system characteristics are discussed in the report.

Given this, the harmonic emission limits for installation (i) expressed in terms of current are given by:

$$E_{Ihi} = \min\left(\frac{1}{Z_{hB}} \cdot \frac{U_N^2}{S_i} \cdot K_{hB} \cdot G_{hLV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \quad ; \quad \frac{1}{Z_{hi}} \cdot \frac{U_N^2}{S_i} \cdot G_{hLV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \right)$$

where:

- E_{Ihi} is the harmonic current emission limit for the installation (i) connected at LV (% of installation nominal current);
- Z_{hB} is the harmonic impedance of the supply system at the LV busbar;
- Z_{hi} is the harmonic impedance of the supply system at the installation level;
- U_N is the nominal phase-to-phase voltage of the LV system;
- other variables are defined before.

This approach does not take into account resonance at the LV level. For cases where resonance might occur, more detailed assessment or simulation methods would be needed.

Case of unbalance

Concerning voltage unbalance, the same approach as for harmonics is used to define emission limits for large three-phase installations connected at LV. The report does not address the allocation of unbalance emission limits to single phase installations, as the physical connection to the network should be managed by the system operator or owner. Voltage unbalance resulting from line impedance asymmetries is generally negligible at LV.

Case of flicker

For flicker, the approach applied at LV is the same as at MV, without considering an additional condition at the LV busbar level. It is to be noted that the limits defined in IEC product family standards aim to limit the Pst to 1,0 with a maximum reference or declared system impedance. In general, the pieces of equipment are connected at locations with lower values of the system impedance, so that the planning levels are often not exceeded. However, when one or several pieces of equipment complying with IEC 61000-3-11 are connected to the same part of a system, it may happen that the resultant flicker level is higher than the calculated share for existing installations. In this case, the emission limits for new installations could be reduced or the system flicker absorption capacity could be increased.

CONDITIONAL ACCEPTANCE OF HIGHER EMISSION LEVELS

The guidelines described above are based on simplifying assumptions that may not provide the optimum solution for all situations, so they should be used with flexibility and judgment as far as engineering is concerned. Under some circumstances, the system operator or owner may accept a disturbing installation to emit disturbances beyond the basic limits set using the above procedures.

This so-called stage 3 assessment considers that various factors may leave a margin on the system for accepting higher emission limits. For example, some of the available supply capacity of the system may not be utilized for a period of time, the general summation law may be too conservative, or higher disturbance levels may be allowed in some part of the system after reallocation of planning levels.

To this end, a detailed study should be carried out, taking account of the pre-existing disturbance levels and of the expected contribution from the considered installation for different operating conditions. As a result, the parties may agree on special conditions that facilitate connection of the disturbing installation.

CONCLUSIONS AND FUTURE WORK

At the time of the preparation of this paper, the joint working group has delivered three technical reports to IEC for updating and supplementing international recommendations on emission limits for the connection of disturbing installations. The fourth report will follow in 2007. The adoption process is under the IEC responsibility.

The methods given in the technical reports are more detailed than the principles summarized in this paper. It is expected that once published these reports will provide a comprehensive approach for enabling system operators or owners to set emission limits that can be adapted to different system characteristics while allowing coordination of disturbances between the different voltage levels of a supply system.

The scope of the working group also includes the preparation of a synthesized report as a separate deliverable for Cigré in 2007 for publication in Electra. A new joint task force CIGRE/CIRED C4.109 (Emission Assessment Techniques) has also been established to document practical techniques for the post-connection assessment of emission levels from a given customer installation, based on the revised definition recommended by C4.103.

REFERENCES

[1] IEC 61000-3-6, 1996, "Assessment of emission limits for distorting loads in MV and HV power systems".

[2] IEC 61000-3-7, 1996, "Assessment of emission limits for fluctuating loads in MV and HV power systems".

[3] R. Koch, G. Beaulieu, L. Berthet, M. Halpin, 2007, "International Survey Of Unbalance Levels In LV, MV, HV, and EHV Power Systems: CIGRE/CIRED JWG C4.103 Results ", *CIRED 2007, Vienna, Austria.*

[4] CIGRE/CIRED JWG C4.07, 2004, *Power Quality Indices and Objectives,* Cigré Technical Brochure TB261, Paris, France.

Acknowledgments

The authors acknowledge the excellent contributions of members of JWG C4.103, and the transmission and distribution companies that made measured unbalance data available for analysis by the working group.