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# **POWER QUALITY INDICES AND OBJECTIVES**

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**POWER QUALITY INDICES AND OBJECTIVES**

**Final WG Report**

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# 1 INTRODUCTION AND SCOPE

As a result of the opening up of the electricity markets, system operators are being increasingly encouraged to report more and more to external parties, namely users and regulators, information relating to power system performance. Whereas in the past, power quality was often seen as an implicit duty on system operators, today quality objectives have become more and more explicit either in the form of contracts negotiated with customers, or in the form of definite objectives agreed with the regulator. Indeed a number of regulators already have defined, or plan to establish, power quality objectives (e.g. supply continuity and voltage quality) to be met by the electricity supply systems. In some countries, regulators may even impose penalties in cases of non-observance of the power quality objectives. It is an important feature of meeting power quality targets that the interested parties agree on the method(s) of gathering and presenting power quality data.

This report presents power quality data gathered from several different countries across a number of monitoring points over a number of years. The report provides guidance on the key factors that need to be considered when gathering and presenting data. In so doing the report considers the benefits of consistency but recognises the inherent differences between different electrical systems and different power quality objectives. The report develops the case for a consistent set of power quality indices and objectives that can be seen as the outer envelope of performance for each power quality parameter. Relevant power quality indices are prerequisites for assessing site and system performance with respect to power quality. Such indices will eventually facilitate the task of system operators with their obligation to routinely report power quality performance. Some site indices have already been defined in standards, but others are still missing - in particular for high and extra-high voltage (HV-EHV) systems. Since system operators are at risk of being exposed to penalty payments for excursions in quality beyond the objective values (limit values of the index) it is important that the objectives are seen not only as achievable but also as being cost effective for all customers. This adds to the incentive for having well defined and recognized power quality indices.

Optimizing the power quality performance of the electrical system is one of the roles of a system operator, the role of the regulator is to ensure that this is carried out in a cost-effective manner in that if customers expect power quality to be an intrinsic characteristic of the product they also want it at the lowest price. Recognizing that historically the electrical systems in different countries have been designed in different ways to cater for national / regional variations, e.g. different commercial or climatic conditions, it is essential that any sets of internationally agreed power quality objectives also recognize these differences.

The joint working group CIGRE C4.07/ CIREN was formed in 2000 with the task of researching available power quality measurement data and existing indices for MV, HV and EHV systems<sup>1</sup> with the intention of recommending a set of internationally relevant power quality indices and objectives. The scope of the working group is given in annex A. It is expected that once published these indices will help facilitate the future presentation of power quality data to third parties, typically regulators and customers. The working group did not perform any measurements itself but collected survey results from past or ongoing surveys.

The starting point of the working group activities was the evaluation of the indices and objectives for planning levels proposed in the technical reports IEC 61000-3-6 [1] and 7 [2] concerning harmonics and flicker, with a possible extension of these concepts to voltage unbalance. It is also a part of the scope of the working group to make recommendations for future voltage characteristics for HV and EHV. Additionally, the working group discussed indices for two other significant types of disturbances, voltage dips and interruptions.

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<sup>1</sup> Unless otherwise specified in this report, definitions of LV, MV, HV and EHV are indicative and based on ref. [1]: LV is 1 kV or less, MV is from 1kV to 35 kV included, HV is from 35 kV to 230 kV included, and EHV is higher than 230kV.

Chapter 2 of this report provides an overview of existing indices and objectives for the purpose of highlighting most common denominators among existing indices and objectives. Chapter 3 consists of a review of the measurement results gathered by the working group for providing a basis for the revision of some power quality objectives. Recommendations are given in chapter 4 and 5. In order to fulfil deliverables of the working group, indications on which power quality indices monitors should be able to measure are given along with the conclusions of the report. Further details on the measurement data can be found in annex B.

## 2 OVERVIEW OF EXISTING INDICES AND OBJECTIVES

Considering the scope of the present work, the following overview relates to power quality indices and objectives in their application to characterize power system disturbance levels as such. Such indices and objectives may be defined in the form of so-called “voltage characteristics” that apply to public networks; existing standards cover low and medium voltage (LV – MV) [5]. Also considered are the internal quality objectives, so-called “planning levels”, that system operators may use at MV, HV and EHV for controlling the overall effect due to emissions from disturbing loads as a whole connected to power systems. In addition, various existing national standards or guidelines addressing these topics are included for comparison, with the aim of highlighting the most common denominator among them.

### 2.1 Harmonics

#### 2.1.1 EXISTING INDICES

Obtaining harmonic indices consists of a number of steps: obtaining the spectrum of voltage or current over a given window of time; obtaining a site index from the spectra over a given period; and eventually obtaining a system index from the site indices. Various methods for obtaining the spectrum are being discussed in the technical literature, but the method almost exclusively used in power quality monitoring is the Fourier transform. A number of international standard documents define the measurement process, including IEC 61000-4-7 [3], and the recent 61000-4-30 [4]. Note that descriptions that follow are admittedly incomplete and only for reference purposes. For details, the reader should refer to the latest versions of the various documents.

The method proceeds as follows:

- obtain the spectrum over a 10-cycle (50 Hz systems) or 12-cycle (60 Hz systems) window. The window shall be synchronized to the actual frequency during the measurement;
- the spectra are combined (RMS) to a spectrum over a 3-second interval (150 cycles for 50 Hz systems and 180 cycles for 60 Hz systems) and the so obtained values are referred to as “**very short time**” indices ( $U_{h,vs}$ );
- the 3-second values are combined to a 10-minute value and referred to as “**short time**” indices ( $U_{h,sh}$ );
- 3-second and 10-minute values are evaluated over a one-day or a one-week period depending on the index.

The 95%, 99% or maximum values of the distributions are used as site-indices.

Other publications propose more specific indices such as:

#### Technical report IEC 61000-3-6:1996 [1] :

1. The greatest **95 % probability daily** value of  $U_{h,vs}$  (rms value of individual harmonic components over "very short" 3 s periods);
2. The **maximum weekly** value of  $U_{h,sh}$  (rms value of individual harmonics over "short" 10 min periods);
3. The **maximum weekly** value of  $U_{h,vs}$ .

For measurements it refers to IEC 61000-4-7 [3]. The minimum measurement period should be one week.

**Standard IEC 61000-4-30:2003** [4] also refers to IEC 61000-4-7 [3] for measurements, more specifically to class 1, 10/12-cycle gapless harmonic sub-group measurement, denoted  $C_{n-200-ms}$ . The standard does not

specify indices, but various indices are given as guidelines for contractual applications in the informative annex A.6 of [4] as follows:

1. The number, or percentage, of values during the interval that exceed contractual values might be counted;
2. And/or the worst-case values might be compared to contractual values (the measurement interval might be different for this possibility, for example one year);
3. And/or one or more 95 % (or other percentage) probability weekly values for 10-minute values, and/or 95 % (or other percentage) probability daily values for 3-sec time interval values, expressed in percent, might be compared to contractual values.

Other evaluation techniques might be agreed between the parties. A minimum assessment period of one week is recommended for 10-min values, and daily assessment of 3-sec values for at least one week.

**Standard EN 50160:1999** [5], stipulates that during each period of one **week**, the percentile **95%** of the 10-min mean rms value ( $U_{h,sh}$ ) of each individual harmonic voltage is the quality index to be compared to the relevant voltage characteristic.

Other regional or national standards and guidelines such as NRS048-2:1996 [6], Emeraude contract [8], ER G5/4 [9] or H.-Q. Voltage Characteristics [10] also recommend indices that are often similar to those mentioned above.

### 2.1.2 COMPARISON OF HARMONIC INDICES

Table 1: provides a summary comparison of harmonic indices between various standards and guidelines. It shows that in most cases the reference standard to perform harmonic measurements is IEC 61000-4-7. Practically, the most common index for harmonic voltage is the so-called short time or 10-min value ( $U_{h,sh}$ ). It is used mainly for voltage characteristics and the level of harmonics to be compared with the objectives is usually the value corresponding to 95% probability of weekly statistics.

With regard to planning levels, indices are defined in more details in IEC 61000-3-6 because the aim there is to define emissions and this requires a closer control of the higher levels of disturbances allowed for very short time periods (e.g.: for the so-called 3-sec. very short time interval,  $U_{h,vs}$ : 95% daily and max. weekly are proposed). It is worth noting however that for maximum values, these are likely to be inflated by transients such as transformer switching. Therefore care must be exercised when using maximum values for indices (in practice this problem is sometimes overcome using 99% instead of the maximum value).

| HARMONIC VOLTAGE INDICES                 |                              | International standard or guidelines            |   | Regional or national standards and guidelines      |  |  |                                |  |                                       |
|--|------------------------------|---|---|--|--|--|--------------------------------|--|---------------------------------------|
| Standard / Document                      |                              | IEC 61000-3-6: 1996 [1]                         | IEC 61000-4-30:2003 [4]   | EN50160:1999 [5]                                   | ANSI/IEEE 519:1992 [7]   | NRS048-2:2003 [6]                      | EDF Emeraude contract [8]      | ER G5/4: [9]                               | H.-Q. Voltage Characteristics [10]    |
| <b>Status</b>                            |                              | Technical report type 3                         | International Standard  | European standard                                  | ANSI Std. Recommended practice                                     | National standard                      | Power quality contract         | National Standard                          | Voluntary                             |
| <b>Where it applies</b>                  |                              | International                                   | International   | 19 European countries                              | Some countries mostly in America                                   | Southern African countries             | France                         | UK Countries                               | Québec, CA                            |
| <b>Purpose</b>                           |                              | Indicative planning levels for emission limits. | Power quality measurement methods   | Supply Voltage characteristics for public networks | Recommended practice for emission limits and systems design values | Minimum standard used by the regulator | Supply voltage characteristics | Planning levels for controlling emissions. | Supply voltage characteristics        |
| <b>Indices / assessment</b>              | <b>Very short time (3-s)</b> | $U_{h,vs}$<br><b>95% daily</b>                  | $U_{h,vs}$<br><b>(X% as agreed)</b>   |  | <b>No definite indices</b>   |  |                                |  |                                       |
|  | <b>Short time (10-min)</b>   | $U_{h,sh}$<br><b>Max. weekly</b>                | $U_{h,sh}$<br><b>(X% as agreed)</b>   | $U_{h,sh} + THD$<br><b>95% weekly</b>              |  | $U_{h,sh} + THD$<br><b>95% weekly</b>  | $U_{h,sh} + THD$<br><b>Max</b> |  | $U_{h,sh} + THD$<br><b>95% weekly</b> |
|  | <b>Other</b>                 | $U_{h,vs}^*$<br><b>Max. weekly<sup>2</sup></b>  |   |  | <b>95% (P519A)</b>   |  |                                | $U_{h,1-min} + THD$<br><b>95% weekly</b>   |                                       |
| <b>Period for statistical assessment</b> |                              | One week minimum                                | At least one week or more as agreed   | One week   | Undefined  | One week min.                          | At least one week or more      | One week                                   | One week                              |
| <b>Measurement method</b>                |                              | IEC 61000-4-7                                   | IEC 61000-4-7   | IEC 61000-4-7                                      | No specific measurement method                                     | Specific measurement method            | IEC 61000-4-7                  | Specific measurement method                | IEC 61000-4-7                         |
| <b>Remarks</b>                           |                              | Covers MV to EHV (* Factor 1,5 -2 allowed).     | Indices proposed as guidelines for contractual applications in informative annex A6 | Applies to LV and MV.                              | Covers LV to EHV. Currently under revision.                        | Covers LV-MV HV-EHV.                   | Covers LV-MV HV-EHV.           | Applies to LV-MV and to HV-EHV             | Applies to LV-MV and to HV-EHV        |

Table 1: Summary comparison of harmonic indices between different standards and guidelines.

<sup>2</sup> A factor of 1.5 to 2 is allowed for such a maximum values.

### 2.1.3 EXISTING OBJECTIVES

Before comparing numbers used as power quality objectives, it may be worth recalling some fundamentals of different type of objectives that apply to public power systems.

#### ➤ **Compatibility levels**

*Compatibility levels* only exist at LV and MV. These are disturbance levels used as reference for coordinating the emission and the immunity of equipment which is part of, or supplied by, a supply network in order to ensure the electromagnetic compatibility in the whole system (including network and connected equipment). Compatibility levels are generally based on a high probability of not being exceeded (for example 95%) using distributions which represent both time and space variations of disturbances into the whole system. No specific assessment methods are defined for compatibility levels. For medium voltage, compatibility levels are given in recent standard IEC 61000-2-12 [11].

Note that some national standards or guidelines may also be using the expression “compatibility levels” to actually designate voltage characteristics. When such is the case, the word “limits” will be used instead in this report in order to avoid confusion with compatibility levels normally specified in IEC standards.

#### ➤ **Voltage characteristics**

*Voltage characteristics* are limits or values within which any user can expect the voltage characteristics to remain under normal operating conditions; they do not describe however the typical situation for a customer connected to a public supply network as the actual disturbance level may be much lower. Cenelec EN 50160:1999 [5] defines and describes the main characteristics of the voltage at the customer's supply terminals in public LV and MV electricity distribution systems. Some regional or national recommendations such as NRS 048-2 [6], Emeraude Contract [8], H.-Q. Voltage Characteristics [10] also fall in this category, however these may also apply to higher voltage levels up to EHV.

#### ➤ **Planning levels**

Planning levels are specified by the utility for different voltage levels of the system and can be considered as internal quality objectives of the system operator that can be used for planning purposes in evaluating the impact of all disturbing loads on the supply system. IEC 61000-3-6:1996 [1] defines planning levels, but only indicative values are given because planning levels are internal objectives of the system operator that may differ from case to case, depending on network structure and circumstances.

Table 2 and Table 3 show harmonic voltage objectives from different standards or guidelines.

| HARMONIC VOLTAGE OBJECTIVES |                      | International standards or guidelines                                    |  | Regional or national standards or guidelines       |   |  |  |  |   |                                     |                                     |
|-----------------------------|----------------------|--|--|--|---|--|--|--|---|-------------------------------------|-------------------------------------|
| Standard / Document         |                      | IEC 61000-2-12: 2003 [11]  | IEC 61000-3-6: 1996 [1]                              | CENELEC EN50160:1999 [5]                           | ANSI/IEEE 519:1992 [7]                                      | NRS048-2:2003 [6]                      | EDF Emeraude contract – A. 2 [8]               | ER G5/4:2001 [9]   | H.-Q. Voltage characteristics [10]            |                                     |                                     |
| <b>Purpose</b>              |                      | Defines compatibility levels for MV public networks                      | Indicative Planning levels for controlling emissions | Supply voltage characteristics for public networks | Recommended practice for emissions and system design values | Minimum standard used by the regulator | Supply voltage characteristics                 | Planning levels for the connection of non-linear equipment to public network | Information on supply voltage characteristics |                                     |                                     |
| <b>Objectives MV</b>        | <b>Voltage level</b> | 1 to 35 kV   | 1 to 35 kV   | 1 to 35 kV   | 120V to 69kV  | 1 to 44 kV                             | 1 to 50kV                                      | 6.6 to 20 kV   | 0,75 to 34,5 kV                               |                                     |                                     |
|                             | <b>Order</b>         | $h \leq 50$  | Typically $h \leq 40$                                | $h \leq 25$  | All order   | $h \leq 40$                            | $h \leq 25$                                    | $h \leq 50$  | $h \leq 25$ +THD                              |                                     |                                     |
|                             | <b>Levels</b>        | <b>Odd</b>   | (e.g.: 6% at $h=5$ )<br>See Table 3                  | (e.g.: 5% at $h=5$ )<br>See Table 3                | (e.g.: 6% at $h=5$ )<br>See Table 3                         | 3% all order                           | (e.g.: 6% at $h=5$ )<br>See Table 3            | (e.g.: 6% at $h=5$ )<br>See Table 3  | (e.g.: 3% at $h=5$ )<br>See Table 3           | (e.g.: 6% at $h=5$ )<br>See Table 3 |                                     |
|                             |                      | <b>Even</b>  |  |  |   | 3% all order                           |  |  |   |                                     |                                     |
| <b>THD</b>                  | 8%                   | 6,5%   | 8%   | 5%   | 8%  | 8%                                     | 4%   | 8%   |   |                                     |                                     |
| <b>Objectives HV-EHV</b>    | <b>Voltage level</b> | Not applicable   | >35 kV   | Not applicable                                     | >69 to 161 kV   | >161kV                                 | > 44 to $\leq 400$ kV                          | >50 kV   | 20 to 400 kV                                  | $\geq 44$ to $\leq 315$ kV          |                                     |
|                             | <b>Order</b>         |  | Typically $h \leq 40$                                |  | All order   |  | $h \leq 40$                                    | $h \leq 25$  | $h \leq 50$                                   | $h \leq 50$ +THD                    |                                     |
|                             | <b>Levels</b>        | <b>Odd</b>   |  | (e.g.: 2% at $h=5$ )<br>See Table 3                |   | 1,5%                                   | 1%   | (e.g.: 2% at $h=5$ )<br>See Table 3  | (e.g.: 2% at $h=5$ )<br>See Table 3           | (e.g.: 2% at $h=5$ )<br>See Table 3 | (e.g.: 2% at $h=5$ )<br>See Table 3 |
|                             |                      | <b>Even</b>  |  |  |   | 1,5%                                   | 1%   |  |   |                                     |                                     |
| <b>THD</b>                  |                      | 3%   |  | 2,5%   | 1,5%  | 3%                                     | 3%   | 3%   | 3%  |                                     |                                     |
| <b>Remarks</b>              |                      | Higher levels (THD up to 11%) are specified for very short time effects. | Covers MV to EHV.                                    | Applies to LV and MV only                          | Standard currently under revision                           |  | Objectives for harmonics at HV are informative | Objectives for harmonics are informative                                     |   | Covers LV-MV and HV-EHV             |                                     |

Table 2: Summary comparison of harmonic voltage objectives between different standards and guidelines.

| MV – Harmonic Voltages (% of fundamental or declared voltage) |                                    |  |                                      |                                    |                              |                                  | HV-EHV – Harmonic Voltages (% of fundamental or declared voltage) |   |                       |                             |                 |                                 |         |                             |
|---|------------------------------------|--|--------------------------------------|------------------------------------|------------------------------|----------------------------------|---|---|-----------------------|-----------------------------|-----------------|---------------------------------|---------|-----------------------------|
| Order h   | Comp. levels (IEC 61000-2-12) [11] | Voltage Char. (EN 50160 + Emeraude cont.) [5][8] | Voltage Charact. (NRS 048-2:2003)[6] | Planning levels (IEC 61000-3-6)[1] | Planning levels (ER G5/4)[9] | Voltage Limits. (IEEE 519:92)[7] | Order h   | Planning levels (IEC 61000-3-6 NRS 048-2) [6] | Emeraude contract [8] | Planning levels ER G5/4 [9] |                 | Voltage Limits. IEEE 519:92 [7] |         | Voltage charact. (H-Q) [10] |
|   |                                    |  |                                      |                                    |                              |                                  |   |   |                       | > 20 < 145 kV               | 275 – 400 kV    | >69-161 kV                      | >161 kV |                             |
| 2   | 2                                  | 2  | 2                                    | 1,6                                | 1,5                          | 3                                | 2   | 1,5   | 1,5                   | 1                           | 1               | 1,5                             | 1       | 1,5                         |
| 3   | 5                                  | 5  | 5                                    | 4                                  | 3                            | 3                                | 3   | 2   | 2                     | 2                           | 1,5             | 1,5                             | 1       | 2                           |
| 4   | 1                                  | 1  | 1                                    | 1                                  | 1                            | 3                                | 4   | 1   | 1                     | 0,8                         | 0,8             | 1,5                             | 1       | 1                           |
| 5   | 6                                  | 6  | 6                                    | 5                                  | 3                            | 3                                | 5   | 2   | 2                     | 2                           | 2               | 1,5                             | 1       | 2                           |
| 6   | 0,5                                | 0,5  | 0,5                                  | 0,5                                | 0,5                          | 3                                | 6   | 0,5   | 0,5                   | 0,5                         | 0,5             | 1,5                             | 1       | 0,5                         |
| 7   | 5                                  | 5  | 5                                    | 4                                  | 3                            | 3                                | 7   | 2   | 2                     | 2                           | 1,5             | 1,5                             | 1       | 2                           |
| 8   | 0,5                                | 0,5  | 0,5                                  | 0,4                                | 0,4                          | 3                                | 8   | 0,4   | 0,5                   | 0,4                         | 0,4             | 1,5                             | 1       | 0,4                         |
| 9   | 1,5                                | 1,5  | 1,5                                  | 1,2                                | 1,2                          | 3                                | 9   | 1   | 1                     | 1                           | 0,5             | 1,5                             | 1       | 1                           |
| 10  | 0,5                                | 0,5  | 0,5                                  | 0,4                                | 0,4                          | 3                                | 10  | 0,4   | 0,5                   | 0,4                         | 0,4             | 1,5                             | 1       | 0,4                         |
| 11  | 3,5                                | 3,5  | 3,5                                  | 3                                  | 2                            | 3                                | 11  | 1,5   | 1,5                   | 1,5                         | 1               | 1,5                             | 1       | 1,5                         |
| 12  | 0,46                               | 0,5  | 0,46                                 | 0,2                                | 0,2                          | 3                                | 12  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 13  | 3                                  | 3  | 3                                    | 2,5                                | 2                            | 3                                | 13  | 1,5   | 1,5                   | 1,5                         | 1               | 1,5                             | 1       | 1,5                         |
| 14  | 0,43                               | 0,5  | 0,43                                 | 0,2                                | 0,2                          | 3                                | 14  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 15  | 0,4                                | 0,5  | 0,4                                  | 0,3                                | 0,3                          | 3                                | 15  | 0,3   | 0,5                   | 0,3                         | 0,3             | 1,5                             | 1       | 0,75                        |
| 16  | 0,41                               | 0,5  | 0,41                                 | 0,2                                | 0,2                          | 3                                | 16  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 17  | 2                                  | 2  | 2                                    | 1,6                                | 1,6                          | 3                                | 17  | 1   | 1                     | 1                           | 0,5             | 1,5                             | 1       | 1                           |
| 18  | 0,39                               | 0,5  | 0,39                                 | 0,2                                | 0,2                          | 3                                | 18  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 19  | 1,76                               | 1,5  | 1,76                                 | 1,2                                | 1,2                          | 3                                | 19  | 1   | 1                     | 1                           | 0,5             | 1,5                             | 1       | 1                           |
| 20  | 0,38                               | 0,5  | 0,38                                 | 0,2                                | 0,2                          | 3                                | 20  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 21  | 0,3                                | 0,5  | 0,3                                  | 0,2                                | 0,2                          | 3                                | 21  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,5                         |
| 22  | 0,36                               | 0,5  | 0,36                                 | 0,2                                | 0,2                          | 3                                | 22  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 23  | 1,41                               | 1,5  | 1,41                                 | 1,2                                | 1,2                          | 3                                | 23  | 0,7   | 0,7                   | 0,7                         | 0,5             | 1,5                             | 1       | 0,7                         |
| 24  | 0,35                               | 0,5  | 0,35                                 | 0,2                                | 0,2                          | 3                                | 24  | 0,2   | 0,5                   | 0,2                         | 0,2             | 1,5                             | 1       | 0,3                         |
| 25  | 1,27                               | 1,5  | 1,27                                 | 1,2                                | 0,7                          | 3                                | 25  | 0,7   | 0,7                   | 0,7                         | 0,5             | 1,5                             | 1       | 0,7                         |
| Odd non mult. of 3 >25  | 2,27 (17/h) - 0,27                 | n/a  | 2,27 (17/h) - 0,27                   | 0,2 + 1,0 (25/h)                   | 0,2+ 0,5*(25/h)              | 3                                | Odd non mult. of 3 >25  | 0,2 + 0,5 (25/h)                              | n/a                   | 0,2+ 0,5*(25/h)             | 0,2+ 0,3*(25/h) | 1,5                             | 1       | 0,2 + 0,5 (25/h)            |
| THD   | 8                                  | 8  | 8                                    | 6,5                                | 4                            | 5                                | THD   | 3   | 3                     | 3                           | 3               | 2,5                             | 1,5     | 3                           |

Table 3: Summary comparison of individual harmonic voltage between different standards and guidelines.

#### 2.1.4 COMPARISON OF EXISTING OBJECTIVES

Table 3 gives comparison of various harmonic voltage objectives.

For medium voltage systems, the most common harmonic voltage objectives in use correspond to values of standard EN 50160. New standard IEC 61000-2-12 recommends compatibility levels for individual harmonic voltages (long term effects) at MV do not differ from levels given in EN50160 for low order harmonics and slightly differ for high order harmonics.

For high and extra-high voltage transmission systems, it is important to realize the different purpose of voltage quality objectives. In contrast to low voltage systems, quality objectives for harmonics in HV-EHV transmission systems are not directly related to equipment immunity because the end-use equipment is not directly connected at HV-EHV. Indeed, the indicative levels given in IEC-61000-3-6 for HV-EHV systems are well below the levels that could cause immediate disturbances on the equipment. The limits to disturbances on transmission systems are aimed at coordinating disturbance levels between different parts of the system or different voltage levels. Therefore voltage quality objectives at HV-EHV may differ from case to case depending on the system configuration, the transfer characteristics between the different voltage levels (attenuation or amplification), the actual disturbance levels on the system, etc. This corresponds to the definition of planning levels. Voltage characteristics may be equal to or higher than the planning levels, depending on the margin required to ensure that voltage characteristics are not exceeded at any supply point.

A standard such as EN 50160 does not exist for defining voltage characteristics for transmission systems at HV-EHV. There are national standards or regional guidelines however that give indicative values for harmonic voltages at HV-EHV. In most cases, these values correspond to planning levels for HV-EHV published in IEC 61000-3-6, locally adapted to account for specific system configuration or circumstances. In these cases, the required margin between planning levels and voltage characteristics is only indirectly achieved, in general by using less stringent indices for the latter.

Standard ANSI/IEEE 519 also recommends harmonic voltage limits at HV-EHV for system design purposes. For voltage levels higher than 161 kV, this standard recommends harmonic voltage levels that are twice as severe (only 1% for harmonic order 5) than planning levels proposed in IEC-61000-3-6. Another difference is that ANSI/IEEE 519 allows the same level of harmonic voltage for any harmonic order; this may change in the future because this standard is currently under revision.

## 2.2 Flicker

Voltage fluctuations cause changes of the luminance of lamps which can create the visual phenomenon called flicker. The degree of unsteadiness of human visual sensation via a lamp, called "*flicker*", is strictly related to the fluctuation of the voltage supplying the lamp, the characteristics of the lamp and the physiology of the eye-brain of the person involved. In order to standardise the flicker evaluation an international definition of an instrument has been developed.

The flickermeter algorithm as defined in IEC 61000-4-15 [12] results in:

- a **10-minute "short-term flicker severity -  $P_{st}$ "**. This value is obtained from a statistical analysis of the "instantaneous flicker value" in a way which models incandescent lamps and our observation of light intensity variations.
- From the 10-minute value, a **2-hour "long-term flicker severity -  $P_{lt}$ "** is calculated.

Indices of flicker severity ( $P_{st}$  and  $P_{it}$ ) are expressed in per unit of the irritability threshold of flicker, that is the level of flicker considered irritable by a significant portion of the people involved in the tests.

### 2.2.1 EXISTING INDICES

**Publication IEC 61000-3-7:1996** [2] refers to IEC 61000-4-15 [12] (formerly IEC 868) for measurements. The minimum measurement period should be one week. For flicker, indices should be:

1.  $P_{st}$  **99% weekly**;
2.  $P_{it}$  **99% weekly**.

**Standard IEC 61000-4-30** [4] also refers to standard IEC 61000-4-15 for flicker measurement (class A performance). Voltage dips, swells, and interruptions shall cause  $P_{st}$  and  $P_{it}$  output values to be flagged so that they can later be removed from statistics.  $P_{st}$  or  $P_{it}$  might be considered. The minimum assessment period should be one week. The following techniques are suggested in an informative annex, but here too, other evaluation techniques might be agreed between parties:

1. The number, or percentage, of values during the interval that exceed contractual values might be counted;
2. And/or a 99 % (or other percentage) probability weekly values for  $P_{st}$ , or 95 % (or other percentage) probability weekly value for  $P_{it}$ , might be compared to contractual values.

In Cenelec **EN 50160**, the index to be used is the **weekly  $P_{it}$  for 95 %** of the time.

A number of other regional or national standards and guidelines such as NRS 048-2:2003 [6], Emeraude contract [8], ER P28 [13] or H.-Q. Voltage Characteristics [10] also recommend indices, some of which are similar to the above. Standard **NRS-048-2:2003** also applied a **weekly  $P_{it}$  for 95%** of the time. High  $P_{st}$  values that are known to have occurred at the time of a voltage dip should be removed from the data.

**The Emeraude contract** specifies that the flicker measurements (index  $P_{it}$ ) should be carried out according to IEC 61000-4-15 (formerly IEC 868). No further specifications are given.

### 2.2.2 COMPARISON OF FLICKER INDICES

**Table 5** provides a summary comparison of flicker indices between various standards and guidelines. It confirms that the most common reference for flicker measurement is basically standard IEC 61000-4-15. The 95% or 99% weekly values of  $P_{st}$  or  $P_{it}$  indices are mostly in use. Considering that  $P_{it}$  and  $P_{st}$  values are often correlated by a definite or quasi-constant factor (see next table) related to the characteristics of the disturbing process, it may be questioned whether there is redundancy when specifying both  $P_{st}$  and  $P_{it}$ .

$$P_{it95\%} = 0,84 * P_{st95\%}$$

**Table 4: Example of the relationship between  $P_{it}$  and  $P_{st}$  based on measured values (annex B survey F-18) for 37 sites from LV to EHV situated in the vicinity of arc furnaces.**

It is also worth noting that high probability indices such as  $P_{it99}$  weekly ( $P_{it}$  is refreshed each 2 hours, so that there are 84 values each week. Hence the 99% value may be considered as either the highest of the week or the second) or 99%  $P_{st}$  daily are likely to be inflated by dips unless such events are flagged according to IEC 61000-4-30 and corresponding values for indices are removed from statistical results.

### 2.2.3 EXISTING OBJECTIVES

**Table 6 summarizes the objectives relevant to flicker among different standards and reference documents.**

### 2.2.4 COMPARISON OF EXISTING OBJECTIVES

The definition of flicker severity somewhat dictates the objectives: under laboratory conditions and for the standard lamp (incandescent 60W filament), a flicker severity exceeding unity will feel disturbing to the majority of individuals; a flicker between 0,7 and 1,0 is noticeable, but not disturbing for most. Accordingly, compatibility levels at LV are near unity ( $P_{it}=0,8$  and  $P_{st}=1$ ), while planning levels are slightly lower ( $P_{it}=0,7$  and  $P_{st}=0,9$ ). EN 50160 defines a limit of 1 p.u. for  $P_{it}$  only. In this case, the voltage characteristic for flicker is higher than the compatibility level.

At EHV and HV however, experience showed that coordination of flicker levels can still be achieved with higher planning levels, noting that attenuation of the flicker due to motor loads downstream sometimes makes the transfer coefficient from EHV - HV - MV to LV lower than unity in many cases. Indeed IEC 61000-3-7 already recognises that transfer coefficients can be taken into consideration in setting higher planning levels at HV-EHV (see note under Table 2 in ref. [2]).

Moreover, concerning flicker objectives, it is worthwhile to mention that many researchers report a concern that  $P_{st}$  threshold of 1.0 is too strict, as it is based on laboratory studies. In the field, this level is often exceeded significantly without known problems. Reasons for this include the fact that a daily assessment does not weight daylight hours less severely, the use of lighting technologies other than incandescent, and the influence of other sources of lighting. The practical assessment of flicker, and corresponding indices is an important area of further research, as the cost implications of meeting the  $P_{st}$  requirements of 1.0 is significant for some utilities and/or their customers.

| FLICKER INDICES                          |                            | International standards or guidelines           |   | Regional or national standards and guidelines      |  |  |  |                                    |
|--|----------------------------|---|---|--|--|--|--|------------------------------------|
| Standard / Document                      |                            | IEC 61000-3-7: 1996 [2]                         | IEC 61000-4-30:2003 [4]   | EN50160:1999 [5]                                   | NRS048-2:2003 [6]                      | EDF Emeraude contract – A. 2 [8]       | ER P28: [13]   | H.-Q. Voltage Characteristics [10] |
| <b>Status</b>                            |                            | Technical report type 3                         | International Standard  | European standard                                  | National standard                      | Premium power contract                 | National Standard                                      | Voluntary                          |
| <b>Where it applies</b>                  |                            | International                                   | International   | 19 European countries                              | Southern African countries             | France                                 | UK   | Québec, CA                         |
| <b>Purpose</b>                           |                            | Indicative planning levels for emission limits. | Power quality measurement methods   | Supply Voltage characteristics for public networks | Minimum standard used by the regulator | Supply voltage characteristics         | Planning levels for controlling emissions.             | Supply voltage characteristics     |
| <b>Indices / assessment</b>              | <b>Short term (10-min)</b> | $P_{st}$<br>99% weekly                          | $P_{st}$<br>99% weekly<br>(or X% as agreed)   |  |  |  | $P_{st}$<br>(no further specification)                 |                                    |
|  | <b>Long term (2-hour)</b>  | $P_{it}$<br>99% weekly                          | $P_{it}$<br>95% weekly<br>(or X% as agreed)   | $P_{it}$<br>95% weekly                             | $P_{st}$<br>95% weekly                 | $P_{it}$<br>(no further specification) | $P_{it}$<br>(no further specification)                 | $P_{it}$<br>95% weekly             |
|  | <b>Other</b>               |   | Number or % of values exceeding contractual values                                  |  |  |  |  |                                    |
| <b>Period for statistical assessment</b> |                            | One week minimum                                | At least one week or more as agreed   | One week   | One week min.                          | At least one week or more              | Sufficient to capture full operating cycle of the load | One week                           |
| <b>Measurement method</b>                |                            | IEC 61000-4-15                                  | IEC 61000-4-15  | IEC 61000-4-15                                     | IEC 61000-4-15                         | IEC 61000-4-15 (formerly 868)          | IEC 868  | IEC 61000-4-15                     |
| <b>Remarks</b>                           |                            | Covers MV to EHV.                               | Indices proposed as guidelines for contractual applications in informative annex A6 | Applies to LV and MV.                              | Applies to LV and MV.                  | HTA is 1 to 50kV and HTB > 50kV        | Published in 1989                                      | Applies to LV-MV and to HV-EHV     |

Table 5: Summary comparison of flicker indices between different standards and reference documents.

| FLICKER OBJECTIVES          |                       | International standards or guidelines  |  | Regional or national standards or guidelines       |   |  |  |   |
|-----------------------------|-----------------------|--|--|--|---|--|--|---|
| Standard / Document         |                       | IEC 61000-3-7<br>[2]   | IEC 61000-2-12<br>[11]   | EN50160:1999<br>[5]                                | NRS048-2:2003<br>[6]  | EdF Emeraude<br>contract – A. 2<br>[8] | ER P28:<br>[13]  | H.-Q. Voltage<br>characteristics<br>[10]      |
| <b>Purpose</b>              |                       | Defines planning levels for controlling emissions                                | Defines compatibility levels for MV public networks *  | Supply voltage characteristics for public networks | Minimum standard used by the regulator                                | Supply voltage characteristics         | Planning levels for the connection of disturbing loads | Information on supply voltage characteristics |
| <b>Objectives at MV</b>     | <b>P<sub>st</sub></b> | <b>0,9</b>   | <b>(1,0) **</b>  |  |   | --                                     | <b>V≤132 kV = 1,0</b>                                  |   |
|                             | <b>P<sub>lt</sub></b> | <b>0,7</b>   | <b>(0,8) **</b>  | <b>1,0</b>   | <b>1,0</b>  | <b>1,0</b>                             | <b>V≤132 kV = 0,8</b>                                  | <b>1,0</b>                                    |
| <b>Objectives at HV-EHV</b> | <b>P<sub>st</sub></b> | <b>0,8*</b>  | <b>Not applicable</b>  | <b>Not applicable</b>                              | --  | --                                     | <b>V≤132 kV = 1,0</b><br><b>V&gt;132 kV = 0,8</b>      |   |
|                             | <b>P<sub>lt</sub></b> | <b>0,6*</b>  | <b>Not applicable</b>  | <b>Not applicable</b>                              | --  | <b>1,0</b>                             | <b>V≤132 kV = 0,8</b><br><b>V&gt;132 kV = 0,6</b>      | <b>0,6</b>                                    |
| <b>Remarks</b>              |                       | Covers MV to EHV (* assuming an attenuation factor of 1 between HV-EHV to MV-LV) | ** No compatibility levels for flicker are defined at MV, however it refers to IEC 61000-2-2 for flicker that can be transferred at LV | Applies to LV and MV only                          | High flicker values flagged according to IEC 61000-4-30 to be removed | HTA from 1 to 50 kV and HTB > 50 kV    |  | Covers LV-MV and HV-EHV                       |

Table 6: Summary comparison of flicker objectives between different standards and reference documents.

## 2.3 Unbalance

The unbalance is a condition in a poly-phase system in which the rms values of the line voltages (fundamental component), and/or the phase angles between consecutive line voltages, are not all equal. For a three-phase system, the degree of the inequality should be expressed as the ratios of the negative (NPS) and zero-sequence components to the positive-sequence (PPS) component. Only the negative-sequence component is addressed here because it is often of more concern.

### 2.3.1 EXISTING INDICES

Only the fundamental components shall be used: all harmonic components should be eliminated e.g. by using DFT algorithm. The further processing is defined in a similar way as the harmonic indices discussed before: from 10-cycle (50 Hz) and 12-cycle (60 Hz), to 3-second intervals, to 10-minute intervals. For unbalance also 2-hour values (obtained by combining 10-minute values) are used. The whole measurement and evaluation procedure is defined in detail in IEC 61000-4-30.

Standard **IEC 61000-4-30** suggests in informative annex A.6 that **10-min and/or 2-hr** values be assessed as follows (other evaluation techniques might be agreed between parties):

1. The number, or percentage, of values during the measurement interval that exceed contractual values might be counted;
2. And/or the worst-case values might be compared to contractual values (the measurement interval might be different for this possibility, for example one year);
3. And/or one or more **95 %** (or other percentage) probability **weekly** values, NPS expressed as a percentage of PPS, might be compared to contractual values.

In standard **Cenelec EN 50160** the unbalance index is the **95 %** of the **10-min** mean rms values of the negative phase sequence component of the supply voltage to be assessed during each period of one **week**.

**Cigre 1992 paper 36-203** [14] is a result of the work done within WG 36.05; it was among the first to propose indices as follows:

- At the end of the total observation time (at least a few days including a week-end, preferably one week), the greatest **95%** probability **daily** value of the **3-sec** index shall be compared to the level;
- One additional criterion was left under consideration, waiting for more field experience: the greatest daily value of the **maximum** rms value over **10 min** periods to be compared to the same level.

National standard **NRS 048-2:2003** states that for each phase, the highest 10 minute root-mean-square (rms) value which is not exceeded for **95 %** of the week is noted. The assessment period shall be a minimum of 7 continuous days.

**ANSI Standard C84.1** includes the NEMA MG-1 information as C84.1 Annex 1. In addition to setting the voltage limits at the point of use at  $\pm 10\%$ , that annex calls for derating motor capacity at levels of unbalance greater than 1% and not exceeding 5%. The derating is based on the thermal effects on motors, and are therefore presumed to be related to long-time measurements rather than short-time measurements. The measurement specified is the difference between the average of the three phase magnitudes<sup>3</sup> and the voltage that differs the most from that average, divided by the average (expressed as a percent).

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<sup>3</sup> Phase-to-phase voltages should be used in order to remove the zero-sequence component [15]

### 2.3.2 COMPARISON OF UNBALANCE INDICES

**Table 7** summarises the indices relevant to negative sequence voltage unbalance factor ( $U_{neg}$ ). We can see that 10-min values are most commonly in use. Although different equations may be used for calculating voltage unbalance factor, results should be similar for a given integration time provided they consider negative sequence voltage. Other approximations such as NEMA [15] formula based on the maximum difference between the phase-to-neutral voltages may give poor approximations especially if zero-sequence is not extracted. More accurate formula are given in [4] and [11] for calculating voltage unbalance factor using only the magnitude of the phase-to-phase voltages and should be used instead.

### 2.3.3 EXISTING OBJECTIVES

**Table 8** summarises the objectives relevant to voltage unbalance among different standards and reference documents.

Below are also given some voltage unbalance objectives ( $U_{neg}$ ) in use in other countries:

- **BELGIUM:** The planning limits on MV and HV are the following: for MV = 2%; and for HV = 1%.
- **BRAZIL:** Voltage unbalance should be within 2% .
- **ITALY:** The planning limits on MV and HV are the following: for MV = 2%; for HV = 1%.
- **GERMANY:** According to VDEW 1992, the compatibility level for voltage unbalance is 2 %.
- **USA:** According to ANSI C84.1 Annex 1 and NEMA MG1, for voltage unbalance in excess of 1%, derating of the motor is needed.

### 2.3.4 COMPARISON OF EXISTING OBJECTIVES

At MV, 2% voltage unbalance is almost the same objective in every document with the exception that in some area, the voltage unbalance may be up to 3% (usually in cases where the networks are predominantly single-phase - i.e. single-phase traction, and single-phase distribution). At HV-EHV, objectives vary from 1% to 2%.

| VOLTAGE UNBALANCE INDICES                |                                | International documents   |   | Regional or national standards and guidelines      |  |   |   |                                    |
|--|--------------------------------|---|---|--|--|---|---|------------------------------------|
| Standard / Document                      |                                | IEC 61000-4-30:2003 [4]   | Cigre 1992 Paper 36-203 [14]  | EN50160:1999 [5]                                   | NRS048-2:2003 [6]                      | EdF Emeraude contract – A. 2 [8]            | ER P29: [16]  | H.-Q. Voltage Characteristics [10] |
| <b>Status</b>                            |                                | International Standard  | Cigre 36.05 work  | European standard                                  | National standard                      | Premium power contract                      | National Standard   | Voluntary                          |
| <b>Where it applies</b>                  |                                | International   | --  | 19 European countries                              | Southern African countries             | France                                      | UK  | Québec, CA                         |
| <b>Purpose</b>                           |                                | Power quality measurement methods   | Assessing voltage quality in relation to harmonics, flicker and unbalance | Supply Voltage characteristics for public networks | Minimum standard used by the regulator | Supply voltage characteristics              | Planning levels for controlling emissions.                                  | Supply voltage characteristics     |
| <b>Indices / assessment</b>              | <b>Very-short time (3-sec)</b> |   | $U_{neg\ vs\ 95\% \text{ daily}}$   |  |  |   |   |                                    |
|  | <b>Short time (10-min)</b>     | $U_{neg\ sh\ 95\% \text{ weekly (or as agreed)}}$                                     | $U_{neg\ sh\ Max\ weekly\ (left\ under\ consideration)}$                  | $U_{neg\ sh\ 95\% \text{ weekly}}$                 | $U_{neg\ sh\ 95\% \text{ daily}}$      | $U_{neg\ sh\ (No\ further\ specification)}$ | <b>Maximum value of negative sequence measured over any 1 minute period</b> |                                    |
|  | <b>Long time (2-hour)</b>      | and/or $U_{neg\ lt\ 95\% \text{ weekly (or as agreed)}}$                              |   |  |  |   |   | $U_{neg\ lt\ 95\% \text{ weekly}}$ |
| <b>Period for statistical assessment</b> |                                | At least one week or more as agreed   | Min. of a few days including a week end                                   | One week   | One week min (7 continuous days)       | At least one week or more                   | Sufficient to represent effect on rotating plant (could be a full year)     | One week                           |
| <b>Remarks</b>                           |                                | Indices proposed as guidelines for contractual applications in informative annex A.6. | Covers LV to EHV.   | Applies to LV and MV.                              | Covers LV to HV.                       | 1kV to 50kV and > 50kV                      | Applies at 132 kV and below   | Applies to LV-MV and to HV-EHV     |

Table 7: Summary comparison of voltage unbalance indices between different standards and reference documents.

| VOLTAGE UNBALANCE OBJECTIVES |                         | International documents                      |   | Regional or national standards and guidelines                |  |                                  |  |                                    |
|------------------------------|-------------------------|--|---|--|--|----------------------------------|--|------------------------------------|
| Standard / Document          |                         | IEC 61000-2-12 [11]                          | Cigre 1992 Paper 36-203 [14]  | EN50160:1999 [5]   | NRS048-2:2003 [6]                      | EDF Emeraude contract – A. 2 [8] | ER P29: [16]   | H.-Q. Voltage Characteristics [10] |
| <b>Purpose</b>               |                         | Compatibility levels on public systems at MV | Assessing voltage quality in relation to harmonics, flicker and unbalance | Supply Voltage characteristics for public LV and MV networks | Minimum standard used by the regulator | Supply voltage characteristics   | Planning levels for controlling emissions.   | Supply voltage characteristics     |
| <b>Objectives at MV</b>      | Very short time (3-sec) | -  | 2%  |  |  |                                  |  |                                    |
|                              | Short time (10-min)     | -  | 2%  | 2%   | 2%                                     | 2%                               | 2% (1-min. values)   |                                    |
|                              | Other                   | 2%   | -   |  |  |                                  |  | 2% (2-hr)                          |
| <b>Objectives at HV-EHV</b>  | Very short time (3-sec) | n/a  | 1%  | n/a  |  |                                  |  |                                    |
|                              | Short time (10-min)     | n/a  | 1%  | n/a  | 2%                                     | 1%                               | 2% (1-min. values)   |                                    |
|                              | Other                   | n/a  |   | n/a  |  |                                  |  | HV=1,5% (2-hr); EHV=1% (2-hr)      |
| <b>Remarks</b>               |                         | (up to 3% may occur in some areas)           | Covers LV to EHV.   | (up to 3% in some areas)                                     | (up to 3% may occur in some areas)     | HTA is 1 to 50kV and HTB > 50kV  | Applies at 132 kV and below. Lower emission limits are specified for unbalanced loads. | Covers LV-MV and to HV-EHV         |

Table 8: Summary comparison of voltage unbalance objectives between different standards and reference documents.

## 2.4 Voltage Dips

Voltage dips are a different type of phenomenon to those discussed in previous sections. Where it is possible to evaluate system performance against a harmonic, flicker, or unbalance index over a relatively short time period (e.g. a week), voltage dip performance must be evaluated over a longer period of time (at least one year).

Voltage dips with retained voltage below an interruption threshold (typically 10% of declared voltage, sometimes lower) are in a number of (inter)national standards and guidelines referred to as short interruptions.

### 2.4.1 EXISTING INDICES

#### 2.4.1.1 Indices for individual voltage dips

**IEC 61000-4-30 [4]** provides the first international definition and measurement method for the most common characterization of voltage dips (i.e. in terms of magnitude and duration).

For the measurement of dips, IEC 61000-4-30 states that “*the basic measurement of a voltage dip and swell shall be  $U_{rms(1/2)}$  on each measurement channel ( $U_{rms(1/2)}$  is “the value of the rms voltage measured over one cycle and refreshed each half cycle” (we refer only to class A measurements).*

From the rms voltage as a function of time two basic characteristics can be determined:

- retained voltage or the dip depth;
- and duration.

A voltage dip is characterised by a pair of data, either retained voltage and duration or depth and duration:

- the retained voltage is the lowest  $U_{rms(1/2)}$  value measured on any channel during the dip;
- the depth is the difference between the reference voltage and the retained voltage. It is generally expressed in % of the reference voltage;
- the duration of a voltage dip is the time difference between the beginning and the end of the voltage dip.

#### Other characteristics:

The choice of a dip threshold is essential for determining the duration of the event. This choice of threshold is also important for counting events, as events are only counted as voltage dips when the rms voltage drops below the threshold. Dip threshold can be a percentage of either nominal or declared voltage, or a percentage of the sliding voltage reference, which takes into account the actual voltage level prior to the occurrence of a dip. The user shall declare the reference voltage in use.

Voltage dip envelopes may not be rectangular. As a consequence, for a given voltage dip, the measured duration is dependent on the selected dip threshold value. The shape of the envelope may be assessed using several dip thresholds set within the range of voltage dip and voltage interruption threshold detection. The latter concept also called “*Time Below Specified Voltage Threshold*” is presented in more details in reference [17]. Another method for treating non-rectangular dips is part of IEEE standard 493 [22] and discussed in detail in reference [49]. In the latter method, characteristics

are no longer determined for each individual event, but the rms voltage versus time curves are directly used to obtain a so-called “voltage-sag co-ordination chart”. The method in [49] can be seen as a generalized version of the method proposed in [17].

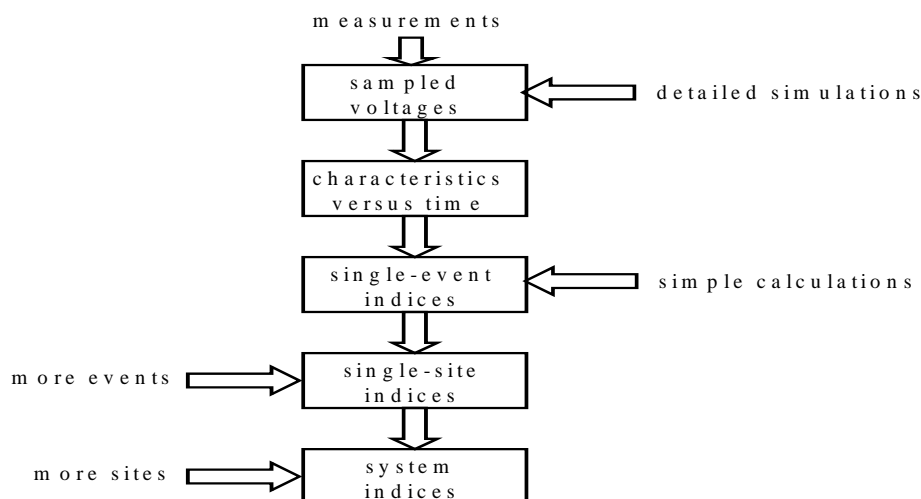
A number of other characteristics for voltage dips are mentioned in an annex to IEC 61000-4-30 including phase angle shift, point-on-wave, three-phase unbalance, missing voltage and distortion during the dip. The use of additional characteristics and indices may give additional information on the origin of the event, on the system and on the effect of the dip on equipment. Even though several of these terms are used in the power-quality literature there is no consistent set of definitions. An unsuccessful attempt was made to define these characteristics and indices in an IEEE standard.

The IEC 61000-2-8 [18] document also refers to the IEC 61000-4-30 for measurement, but introduces a number of additional recommendations for calculating voltage-dip indices. Recommended values are 90% and 91% for dip-start threshold and dip-end threshold, respectively, and 10% for the interruption threshold. Dips involving more than one phase should be designated as a single event if they overlap in time.

#### 2.4.1.2 Voltage sag indices according to IEEE P1564 draft 5 <sup>4</sup>

To give a value to the performance of a power system, as far as voltage sags are concerned, a five-step procedure is proposed in [19]:

- Obtain sampled voltages with a certain sampling rate and resolution.
- Calculate characteristics as a function of time from the sampled voltages.
- Calculate single-event characteristics from the characteristics as a function of time.
- Calculate site indices from the single-event characteristics of all events measured during a certain period of time.
- Calculate system indices from the site indices for all sites within a certain power system.



**Figure 1: The procedure for obtaining voltage sag system indices according to IEEE P1564 draft 5 [19].**

The basic algorithm is shown in Figure 1, where both measurements and calculations may be used as possible sources of information. An example of appropriate single-event indices that can be obtained

<sup>4</sup> This draft can be subject to changes by the time it becomes a standard

from calculations are magnitude and duration. The magnitude can be estimated from a fundamental-frequency complex network theory model, the duration from the fault-clearing time.

The IEEE P1564 draft 5 document uses IEC 61000-4-30 as a base but also introduces two other single-event indices.

The voltage-dip energy is defined as:  $E_{VS} = \int_0^T [1 - V(t)^2] dt$ , with  $V(t)$  the rms voltage in per unit. The integration is taken over the duration of the event, thus for all values of the rms voltage below the threshold. The voltage-sag severity  $S_e$  is defined from the retained voltage  $V$  in per-unit and the duration  $d$  by comparing these values with the so-called SEMI curve. The algorithm for calculating the voltage-sag severity proceeds as follows:

- $d \leq 1$  cycle:  $S_e = 1 - V$
- $1 \text{ cycle} < d \leq 200 \text{ ms}$ :  $S_e = 2(1 - V)$
- $200 \text{ ms} < d \leq 500 \text{ ms}$ :  $S_e = 3.3(1 - V)$
- $500 \text{ ms} < d \leq 10 \text{ s}$ :  $S_e = 5(1 - V)$
- $d > 10 \text{ s}$ :  $S_e = 10(1 - V)$

#### 2.4.1.3 Methods of reporting dip/sag results for a site or for a network

##### ➤ SARFI indices:

A set of voltage dip indices has been suggested in [17] and further defined in IEEE P1564 draft 5. The most commonly-referred to index is the System Average RMS variation Frequency Index or SARFI. The term “RMS variation” is used in US literature to indicate all events in which the rms voltage deviates significantly (typically seen as more than 10%) from its nominal value. This includes voltage dips, voltage swells and long interruptions.

The SARFI<sub>X</sub> index (where X is a number between 0 and 100%) gives the number of events per year with a duration between 0,5 cycle and 1 minute and a retained voltage less than X%. Thus SARFI<sub>70</sub> gives the number of events with retained voltage less than 70%. Strictly speaking SARFI values are obtained as a weighted average over all monitor locations within a supply network or within part of the supply network. However the term is also used to refer to the event frequency at one location. By using the weighting factors, more weight can be given to location with more – or more important – load. The weighting factors are in most cases taken to be equal for all locations.

The SARFI-Curve index (where “Curve” is the name of a predefined curve) gives the number of events per year with a duration between 0,5 cycle and 1 minute, below the predefined curve. For example SARFI-SEMI gives the number of events more severe than the SEMI curve.

Various methods for reporting dips or sags have been proposed in the literature. Such methods may be classified here in two categories: methods to characterise site or system performance as such, and methods most suitable to estimate the compatibility between equipment and supply.

##### ➤ Magnitude-duration table:

Site performance as well as system performance are often described in the form of a voltage-dip table. Different table formats are discussed in IEEE Std. 493 [22] but only the so-called density table is in

common use. The columns of the table represent ranges of voltage-dip duration; the rows represent ranges of retained voltage.

The choice of the magnitude and duration ranges for voltage-dip tables is a point of discussion. Different publications use different values.

The voltage-dip table recommended by the Unipede DISDIP group [50]. is given in Table 9. This table is also included in IEC 61000-2-8 and in IEEE P1564 draft 5.

|        | 20-100ms | 100-150 ms | 0.5-1 sec | 1-3 sec | 3-20 sec | 20-60 sec | 60-180 sec | >180 sec |
|--------|----------|------------|-----------|---------|----------|-----------|------------|----------|
| 85-90% |          |            |           |         |          |           |            |          |
| 70-85% |          |            |           |         |          |           |            |          |
| 40-70% |          |            |           |         |          |           |            |          |
| 10-40% |          |            |           |         |          |           |            |          |
| <10%   |          |            |           |         |          |           |            |          |

**Table 9: Density table, as recommended by Unipede.**

The technical report IEC 61000-2-8 [18] concludes that voltage dips should be classified by depth and duration in accordance with Table 10. Dips that involve more than one phase should be designated as a single event if they overlap in time. This table is also included in IEEE P1564 draft 5.

|        | 1 cycl-0.1s | 0.1-0.25s | 0.25-0.5s | 0.5-1s | 1-3s | 3-20s | 20-60s | 60-180s |
|--------|-------------|-----------|-----------|--------|------|-------|--------|---------|
| 80-90% |             |           |           |        |      |       |        |         |
| 70-80% |             |           |           |        |      |       |        |         |
| 60-70% |             |           |           |        |      |       |        |         |
| 50-60% |             |           |           |        |      |       |        |         |
| 40-50% |             |           |           |        |      |       |        |         |
| 30-40% |             |           |           |        |      |       |        |         |
| 20-30% |             |           |           |        |      |       |        |         |
| 10-20% |             |           |           |        |      |       |        |         |
| <10%   |             |           |           |        |      |       |        |         |

**Table 10: Recommended presentation of results according to IEC 61000-2-8.**

IEC 61000-4-11 prescribes a number of duration and retained voltage values for testing equipment. These values are used in IEEE P1564 draft 5 to define another possible voltage-dip table, see Table 11.

| retained voltage | DURATION OF THE VOLTAGE SAG |                |           |         |          |
|------------------|-----------------------------|----------------|-----------|---------|----------|
|                  | <1 cycle                    | 1 cycle-200 ms | 0.2-0.5 s | 0.5-5 s | 5s-5 min |
| 70-80%           |                             |                |           |         |          |
| 40-70%           |                             |                |           |         |          |
| 10-40%           |                             |                |           |         |          |
| ≤10%             |                             |                |           |         |          |

**Table 11: Presentation of results based on IEC 61000-4-11 according to IEEE P1564 draft 5.**

#### ➤ Voltage-sag co-ordination chart

A method for reporting site information from event magnitude and duration is described in IEEE Std.1346-1998 [21] and in IEEE Std.493-1997[22]. The method results in the so-called “voltage sag coordination chart”. An example of such a chart is shown in Figure 2. This figure is obtained from 6 years of monitoring at 20 HV-sites. The chart, as defined in these standards, contains the performance of the supply at a given site, and the voltage tolerance of one or more devices. For the purpose of this document only the supply performance part of the chart is of relevance. The chart gives the number of

events per year (sags and interruptions) as a function of the severity of the event. For the example shown here there is on average 1 event per year where the voltage drops below 50% for 100 ms or longer. There is also on average 1 event per year more severe than 80%, 80 ms and on average 0.1 event per year below 70% for longer than 500 ms.

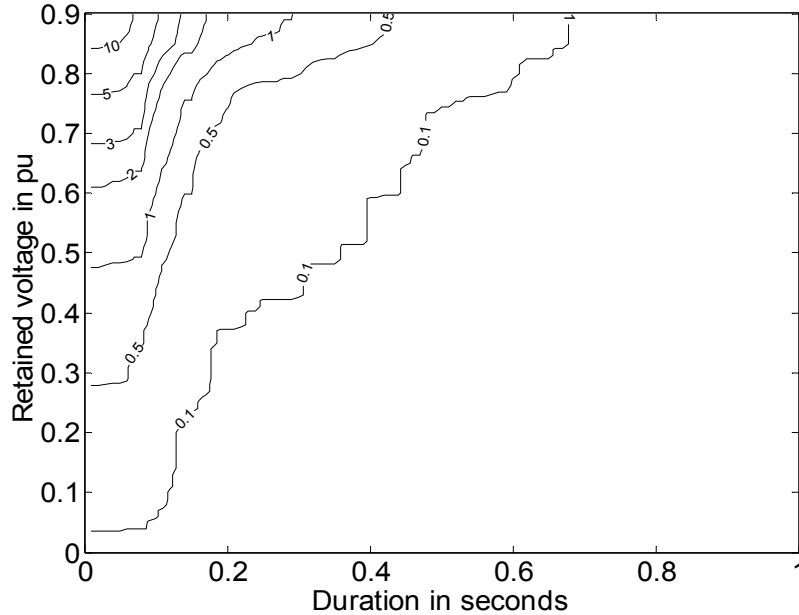


Figure 2: Voltage sag co-ordination chart according the IEEE Std.493 and IEEE Std.1346.

➤ **Dip Performance/Sensitivity Area Plots:**

Some utilities (Eskom and EDF) have developed approaches to defining specific areas on a magnitude/duration plane that attempt to provide generalized guidelines on areas where dips are likely to occur, and areas that customers are likely to be affected by. The aim of these generalized areas is to reduce the number of indices that need to be reported and managed, based on the most "appropriate" grouping of dip events.

| retained voltage U | Duration t        |                    |                 |
|--------------------|-------------------|--------------------|-----------------|
|                    | 20 ≤ t < 150 (ms) | 150 ≤ t < 600 (ms) | 0.6 ≤ t < 3 (s) |
| 90 > U ≥ 85        | Y                 |                    |                 |
| 85 > U ≥ 80        |                   |                    |                 |
| 80 > U ≥ 70        | S                 |                    | Z1              |
| 70 > U ≥ 60        |                   |                    | X1              |
| 60 > U ≥ 40        |                   |                    | X2              |
| 40 > U ≥ 0         | T                 |                    | Z2              |

Table 12: NRS-048-2:2003 dip reporting method.

The categorization method adopted by NRS-048-2:2003 [6] South Africa is shown above. The Y-type (grey) area reflects dips that are expected to occur frequently on typical HV and MV systems, and against which customers should protect their plant. The X-type areas (X1 and X2) reflect "normal" HV protection clearance times and hence a significant number of events are expected to occur in this

area. Customers with sensitive equipment should attempt to protect against at least X1 type dips that are more frequent. The T-type area reflects close-up faults, which are not expected to happen too regularly - and which a utility should specifically address if excessive. S-type dips are not as common as X and Y type events, but may occur where impedance protection schemes are used, or where voltage recovery is delayed. Z-type dips are very uncommon on HV systems (particularly Z2-type events), as this generally reflects problematic protection operation. These may be more common on MV systems. Table 12 is also included in IEEE P1564 draft 5.

The EDF dip reporting method used in contracts makes use of a 70% (retained voltage) threshold and a 600ms duration threshold. Based on line-to-line measurements, this area defines what dips are not likely to occur often, particularly on HV systems (i.e. most single-phase to ground faults and HV dips originating due to faults in the MV network would not exceed the magnitude threshold, and only problematic protection would result in dips exceeding the duration threshold).

#### **2.4.1.4 Comparison of dip indices**

##### **SARFI indices**

Advantages:

- The small number of indices makes it easy to compare different sites, different systems, and year-to-year variations;
- The simplicity of the method means that it easily becomes widely used. The method has in fact become rather popular in the US and in parts of Asia;
- The index depends only on the total number of events. When the indices are used to quantify system performance there will be a strong incentive to reduce the number of faults. This also has a positive effect on the reliability (number of interruptions).

Disadvantages:

- The indices are not relevant for most equipment;
- All information on duration is lost. When the indices are used to quantify system performance, there is no incentive to reduce fault-clearing times;
- The use of the (system) average in the strict definition makes it less appropriate as a system index than as a site index. The method can be adjusted to cover 95 percentile values but that would make it more complicated.

##### **Voltage-dip co-ordination chart**

Advantages:

- The chart can be directly compared with equipment performance. This makes the method very suitable for data exchange between network operator and industrial customer;
- The data can be reprocessed into the format of most other indexing methods without significant loss of information;
- Non-rectangular voltage dips can be included without further complicating the method.

Disadvantages:

- The method is rather complicated which means that almost nobody uses it. The method is therefore certainly not practical for use with domestic customers;
- A simple comparison between sites is not possible because of the many variables involved;
- When used as a system index the average is used which makes it less suitable as an index. The method can be adjusted to cover 95 percentiles but the result would be even more complicated.

**UNIPEDA table**

Advantages:

- The number of indices is limited but there is still a sufficient level of detail for comparison with system performance;
- Voltage-dip tables are easy to understand, which contributes to their wide use. This specific choice of voltage and duration ranges is commonly used;
- The same format can be used for average, 50-percentile, 95-percentile and maximum value;
- The table covers everything from very short dips to long interruptions without any of these being able to overshadow the others;
- It is theoretically possible to include the non-rectangular aspects of voltage dips. This will however require a redefinition of dip duration.

Disadvantages:

- The choice of duration values is not practical with relation to the typical values occurring in practice. Many dips have a duration around 100 ms falling “in between” two cells. The 100-500 ms range (the most populous one in most surveys) is too wide to predict equipment performance;
- The duration ranges between 1 second and 3 minutes hardly ever contain any dips. In most cases these columns can be merged into one or two columns;
- For site and system comparison purposes the table is not practical. Cells can be merged for site indices and for average sites, but not for 95-percentile tables.

**Table according to IEC 61000-2-8**

Advantages:

- It is recommended in an international technical report;
- It has all the advantages of a voltage-dip table (see UNIPEDA table);
- The 100-500 ms range has been split.

Disadvantages:

- The subdivision of the retained voltage into 9 ranges will lead to many empty cells. This table has 72 cells versus 35 in the UNIPEDA table;
- For site and system comparison purposes the table is probably too detailed.

**NRS 048-2:2003 table**

## Advantages:

- A relatively small number of indices. The values in the X, S, T and Z cells enable utility dip-performance reporting;
- It has all the advantages of a voltage-dip table (see UNIPEDA table);
- There is a direct relation with system properties (leading to typical clustering of events) and with equipment immunity properties.

## Disadvantages:

- The table is not commonly used outside Southern-Africa;
- The table stops at 3 seconds.

**Voltage-dip energy index**

## Advantages:

- One single index makes comparison very easy;
- The value of the index is in (milli)seconds which simplifies its understanding;
- The use of this index is picking up already;
- The method can easily be extended to 95-percentile values.

## Disadvantages:

- The method of calculating the index means that one long event may overshadow all other events;
- There is no link at all with equipment performance; the method is not suitable as a site index;
- To calculate the index a number of steps are needed which not everybody follows exactly. Including this index in IEEE Std.1564 will hopefully solve this problem.

**Voltage-dip severity index**

## Advantages:

- One single index makes comparison easy;
- The method includes both voltage and duration without allowing any of them to overshadow the other;
- The use of this index is already picking up;
- The method can easily be extended to 95 percentile values.

## Disadvantages:

- There is no link at all with equipment performance; the method is not suitable as a site index;
- To calculate the index a number of steps are needed (even more than with the voltage-dip energy index) which everybody not exactly follows. Including this index in IEEE Std.1564 will hopefully solve this problem.

## Comparison with a curve

### Advantages:

- One single index makes comparison easy;
- The number of dips below a standard curve (e.g. SEMI or ITIC curve) gives an indication of the performance for a class of equipment;
- By using a curve for a specific customer or device, the number of equipment / process trips can be estimated;
- By using a curve related to certain system properties (e.g. 600 ms, 70% as used by EdF) a good estimator of the system performance is obtained.

### Disadvantages:

- A customer-specific index does not give information for other customers. There is a loss of information;
- The user has to be aware that the number of dips below the curve is not always a good indicator for the number of equipment trips. (Equipment may also trip for dips above the ITIC curve).

## 2.4.2 EXISTING OBJECTIVES

### 2.4.2.1 International standards or guidelines

Suitable voltage-dip objectives are not yet found in international standard documents specifying the environment for public supply systems. The main reasons to explain this situation are the lack of relevant information concerning voltage dips, and the widely different network topologies and operating environments [18].

Some immunity standards define minimum immunity levels to guide users of some equipment connected at low voltages, but as such these cannot be considered directly in this comparison relating to objectives applicable to supply networks.

### 2.4.2.2 National standards or guidelines

In the European standard **EN 50160:1999** the objectives are the same for LV and MV. A voltage dip is defined as an event with a retained voltage between 90% and 1% of the declared voltage and a duration between 0,5 cycle and one minute. Objectives are given in general terms. It states that under normal operating conditions the expected number of voltage dips in a year may be from up to a few tens to up to one thousand. The majority of voltage dips have a duration less than 1 second and a retained voltage above 40%. However more severe voltage dips (lower retained voltage, longer duration) can occur infrequently. In some areas voltage dips with retained voltage between 90% and 85% of the declared voltage can occur very frequently as a result of the switching of loads in customers' installations.

It is worth noting that the document gives so-called "voltage characteristics" which implies that these are values within which any customer can expect voltage characteristics to remain, most of the time. Strictly speaking the above values should thus not be seen as objectives (or compatibility levels) but as a description of the limiting values that could be seen (at the supply terminals) at any installation. However even these values may be exceeded in some very rare cases. One of the reasons for the

lack of objectives is the difficulty in defining suitable site and system indices<sup>5</sup>. The interpretation of the values in EN 50160 remains a point of discussion and many network operators use the document as a reference for the voltage quality in their own network.

The South African standard **NRS 048-2:2003** gives characteristic values for voltage dips in the form of the number of event in each dip category (see Table 12) which have historically not been exceeded at 95% and 50% of the monitored sites in South Africa. The characteristic values are reproduced in Table 13 and Table 14.

| System voltage      | Number of voltage dips per year |     |     |     |     |     |
|---------------------|---------------------------------|-----|-----|-----|-----|-----|
| Dip category->      | X1                              | X2  | T   | S   | Z1  | Z2  |
| 6.6 – 44 kV (rural) | 85                              | 210 | 115 | 400 | 450 | 450 |
| 6.6 – 44 kV         | 20                              | 30  | 110 | 30  | 20  | 45  |
| 44 – 132 kV         | 35                              | 35  | 25  | 40  | 40  | 10  |
| 220 – 765 kV        | 30                              | 30  | 20  | 20  | 10  | 5   |

Table 13: Characteristic number of voltage dips; 95% of sites.

| System voltage      | Number of voltage dips per year |    |    |    |    |    |
|---------------------|---------------------------------|----|----|----|----|----|
| Dip category >>     | X1                              | X2 | T  | S  | Z1 | Z2 |
| 6.6 – 44 kV (rural) | 13                              | 12 | 10 | 13 | 11 | 10 |
| 6.6 – 44 kV         | 7                               | 7  | 7  | 6  | 3  | 4  |
| 44 – 132 kV         | 13                              | 10 | 5  | 7  | 4  | 2  |
| 220 – 765 kV        | 8                               | 9  | 3  | 2  | 1  | 1  |

Table 14: Characteristic number of voltage dips per year; 50% of sites.

The **Emeraude Contract** [8] does not give any limits for the number of voltage dips, but EdF will give information on voltage dips with a duration exceeding 600 ms and a retained voltage less than 70% of the declared voltage. The phase-to-phase voltage is used for the measurement.

## 2.5 LONG INTERRUPTIONS

### 2.5.1 INDICES

Indices used for transmission interruption reporting differ significantly from utility to utility. The indices used can however be divided into the following categories:

- **Number of events:** *actual number of events and the average number of events over the reporting period (i.e. the latter is the frequency of events);*
- **Duration of events:** *average total duration of events over the reporting period and average time to restore supply per interruption at each supply point. The availability of the supply is the converse of the duration and it gives an indication of the relative risk of interruptions;*
- **Severity of events:** *severity of the interruption events over the reporting period (i.e. the size of load affected) and indices estimating the cost impact per event.*

Different indices in use for further characterizing long interruptions are reviewed hereafter.

<sup>5</sup> A second reason is that dips arise from many causes, including lightning and other weather effects, which are outside the control of the transmission or distribution companies.

### 2.5.1.1 Number of interruption and average frequency of event indices

**Number of supply interruptions (Australia):** The number of supply interruptions is defined as a measure of the number of interruptions to customers due to failure to provide transmission services, *including single phase and multi-phase trip operations* [27].

**Number of loss of supply incidents (UK - National Grid, OFGEM):** System events that result in a single or multiple loss of supply. Incidents are reported individually with details of location, time, incident duration, maximum demand lost, and an estimate of the energy not supplied [28]. Anomalous events (see below) are included in the reported figures. Note here that one reported incident may relate to several customers being affected.

**Number of loss of supply incidents - anomalous events (UK - National Grid, OFGEM):** Interruption events which arise as a result from particular connection or running arrangements chosen by customers or from other causes which are not due to NGC equipment. These are also included in the total number of loss of supply incidents, but are specifically identified.

**Average interruption frequency** indices define the average number of events seen per delivery point or customer supply point.

**System average interruption frequency index - SAIFI:** The quotient of the number of interruptions and the number of delivery points.

**System average interruption frequency index - SAIFI (Cigre WG 39.04 definition):** The quotient of the number of interruptions and the number of *delivery and/or reception points* [29].

**System average interruption frequency index for momentary interruptions - SAIFI-MI (Canada):** A measure of the average number of momentary (less than one minute) interruptions that a delivery point experiences during a given year.

**System average interruption frequency index for sustained interruptions - SAIFI-SI (Canada):** A measure of the average number of sustained (greater than one minute) interruptions that a delivery point experiences during a given year.

**Transmission sustained and momentary average interruption frequency index - TSMAIFI (USA):** Average interruption frequency including momentary and sustained interruptions.

### 2.5.1.2 Average interruption duration, restoration time, and availability indices

Average interruption duration indices describe the average duration of all interruptions per delivery point.

**System average interruption duration - SAIDI:** A measure of the average total interruption duration that a delivery point experiences during a given year.

**System average interruption duration - SAIDI (Cigre WG 39.04 definition):** A measure of the average total interruption duration that a *delivery and/or reception point* experiences during a given year [29].

**Customer interruption duration index - CI (Canada):** Some utilities report a customer interruption duration index defined as [10]:

$$CI = \frac{\text{Sum of customer hours interrupted}}{\text{sum of all customers}}$$

This index is derived considering the duration of forced interruptions, planned interruptions and short interruptions (< 1 min).

**Average incident duration (UK):** The average *incident* duration is defined by National Grid (UK) as [28]:

$$\frac{\text{Estimated Total Energy Unsupplied (MW minutes)}}{\text{Total of MW Lost}}$$

**Average interruption time (UNIPED):** A survey based on average interruption time made use of the following definition for this measure [30]:

$$AIT = \frac{8760.60.ENS}{AD} \quad (\text{min / year})$$

where *ENS* is defined as the energy not supplied due to interruptions with network losses excluded (MWh/year) and *AD* is the annual demand for the power system with network losses excluded (MWh/year).

**Average interruption restoration indices** describe the average restoration time per interruption per deliver point.

**System average restoration index - SAIRI:** A measure of the average duration of a delivery point interruption. It represents the average restoration time for each delivery point interruption.

**System average restoration index - SAIRI (Cigre WG 39.04 definition):** The quotient of the interruption duration and the number of delivery and/or reception point interruptions [29].

➤ **Circuit availability indices:**

**Transmission circuit services availability (Australia - SAIR):** The ability of a transmission entity's transmission network to provide transmission services to exit points to the level agreed in its connection agreements with distributors, transmission customers as [27]:

$$1 - \frac{\sum \text{number of interrupted circuit hours}}{\text{Total number of circuits} \times 8760 \text{ hours}}$$

where the *number of interrupted circuit hours* is defined in relation to each circuit in a transmission entity's transmission network, the number of hours during each reporting period in relation to which that circuit is unavailable to provide transmission services to exit points to the level agreed in connection agreements with distributors, transmission customers and generators *and that unavailability interrupts the provision of transmission services to exit points* required by distributors, transmission customers or generators at that time (excluding outages requested by a distributor, transmission customer or generator, but including all planned outages and unplanned outages in relation to the transmission entity's transmission network).

### 2.5.1.3 Interruption severity and cost indices

Interruption severity indices aim at describing the size of the load affected, and are usually based on the energy not supplied as a function of the overall size of the transmission system.

**Energy not supplied (UK - National Grid, OFGEM):** Estimated energy (MWh) not supplied during the year [28].

**Interruption severity index (UNIPED):** A UNIPED survey on transmission and sub-transmission interruption performance defined an interruption severity index as follows [30]:

$$SI = \frac{ENS(10)^5}{AD} \quad (\text{pu})$$

*ENS* is defined as the energy not supplied due to interruptions with network losses excluded (MWh/year) and *AD* is the annual demand for the power system with network losses excluded (MWh/year).

**System minutes (UNIPED):** A UNIPED survey on transmission and sub-transmission interruption performance defined a system minute index as [30]:

$$SM = \frac{ENS \cdot 60}{PL} \quad (\text{min / year})$$

*ENS* is defined as the energy not supplied due to interruptions with network losses excluded (MWh/year), and *PL* as the peak load of the year (MW).

**System minutes (Cigré):** A system minute index is defined by Study Committee 26 as:

$$SM = \frac{ENS \cdot 60}{MSD}$$

*ENS* is defined as the energy not supplied due to disturbance (MWh), and *MSD* as the Maximum System Demand met to date.

**System minutes (Australia-SAIR):** The system minute index (SM) used to report transmission interruption performance in Australia is defined as [27]:

$$SM = \frac{\sum \text{MW Interrupted} \times \text{duration in minutes}}{\text{System Maximum Demand}}$$

*MW Interrupted* is defined as the estimated MW of the load that was interrupted for a total time of duration in minutes. *System Maximum Demand* is defined as the maximum amount of electricity (MW) generated by generators situated in South Australia, and delivered into South Australia via any interconnection between the South Australian electricity network and the electricity network of another State at any time prior to the commencement of the relevant reporting period. It includes energy not supplied to customer as a result of forced outages and unplanned outages caused by faults.

**Interruption cost index (Norway):** The Norwegian electricity regulator (NVE) has recently adopted an "interruption cost" (IC) index defined as [31]:

$$IC = \sum_{m,n} ENS_{m,n} \cdot c_{m,n}$$

*ENS* is the energy not supplied, *c* the average cost per customer category (dependent on notification), *n* the customer category, and *m* the notified vs. un-notified interruptions. The average cost per customer category is fixed annually by the regulator (NVE). The index applies to events that result in an interruption duration of longer than 3 min, all incident types (i.e. both planned and unplanned interruptions) and is applied for all interruptions at network voltages greater than 1kV.

## 2.5.2 CONSIDERATIONS IN THE APPLICATION OF INDICES

The manner in which specific interruptions are dealt with can have a significant effect on the reported statistics. A review of international utility definitions applied when reporting against indices has concluded that these differ significantly from one transmission utility to another. The most significant differences are discussed below. The review has also concluded that the application of the definitions is often not clearly defined. This highlights the need for an international recommendation not only on the indices used, but also to the application of these indices in practice.

### 2.5.2.1 Event Definition

**Delivery point events (Canada):** The point where the energy from the transmission system, is transferred to the distribution system or the retail customer. This point is generally taken as the low voltage busbar at the step-down transformer stations (the voltage is stepped down from a transmission or sub-transmission voltage, which may cover the range of 50-750kV to a distribution voltage of under 50kV but above 2 kV). For customer-owned stations supplied directly from the Transmission System, this point is generally taken as the interface between utility-owned equipment and the customer equipment [32].

**Customer interruption events (New Zealand):** Each supply voltage at a substation is treated separately. If two customers are supplied from a station at the same voltage, these are reported separately. If a customer is interrupted but the customer can be back fed via another system - or the energy made up by the customer generator, system minutes are not counted [33] (The above definition rules in 2000/2001 resulted in Transpower reporting 102 unplanned interruptions, although only 55 actual incidents occurred).

Indices used to report the number of events experienced by a system in a given period (typically one year) may be related to the number of *incidents*, the number of *delivery points* affected, or the number of *customers* affected. The figure below highlights the difference in these definitions, and illustrates the need to consider the differences in how various utilities define the number of events reported.

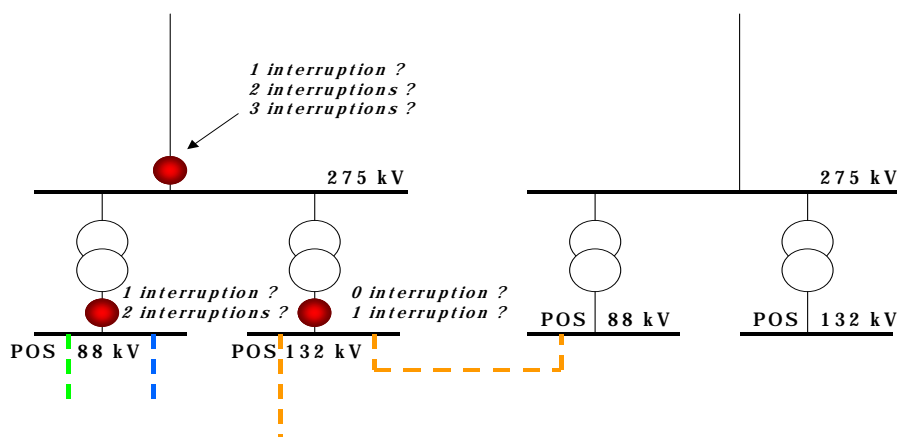


Figure 3: Definition of an interruption event and the impact on the number of events reported.

Figure 3 illustrates another element of the definition of an event which must be considered - i.e. where supply to a transmission supply point is lost but the customer (or distribution wires utility) is able to maintain supply to its customer via an alternative supply.

Consider in the above example, where the number of events are based on (a) the number of *incidents*, (b) the number of *delivery points* affected, and (c) the number of *customers* or *customer feeders* affected. For a 275kV fault, 1 event will be registered using method (a), 1 or 2 events\*, using method (b), and 2 or 3 events\*, using method (c). (\* the latter differences depend on whether the loss of supply to the 132kV busbar can be discounted due to the customer's alternative supply point).

Little information is available on the definition of the above.

#### ➤ Major Events vs. Underlying Events

Major events include extreme weather conditions (e.g. ice storms) and natural disasters (e.g. earthquakes). By their nature, major events may have an overbearing effect on the reported indices. For this reason, some utilities report these separately from underlying events (the majority of smaller events on the system over the reporting period).

**Major events (Cigre definition):** In questionnaires sent out by Cigre on major incidents in the 1970's and again in the 1980's, major incidents were defined as those for which the degree of severity exceeded 1 system minute on systems having a maximum demand in excess of 1000 MW (this was reduced to 500MW in the second survey) [34].

**Major events (USA - DOE):** In the USA, mandatory reporting of major events is required by transmission operators to the Department of Energy. The following criteria define such events.

Any load shedding actions resulting in the reduction of over 100 megawatts (MW) of firm customer load for reasons of maintaining the continuity of the bulk electric power supply system.

Equipment failures and system operational actions associated with the loss of firm system loads for a period in excess of 15 minutes, as described below:

- Reports from entities with a previous year recorded peak load of over 3 000 MW are required for all such losses of firm loads which total over 300 MW;
- Reports from all other entities are required for all such losses of firm loads which total over 200 MW or 50% of the system load being supplied immediately prior to the incident, whichever is less.

Other events or occurrences which result in a continuous interruption for three hours or longer to over 50,000 customers, or more than 50% of the total customers being served immediately prior to the interruption, whichever is less.

**IEEE-1366 (distribution systems):** A major incident is defined for distribution utilities as one in which more than 10% of customers are affected in any 24 hr period. As the term is (later in the document) also used as an interruption cause code, it may in some cases be used by a distribution utility to define a loss of transmission supply. IEEE 1366 allows the exclusion of specific incidents such as: major events, scheduled interruptions, and interruptions out of the control of the utility. The primary aim of this method of reporting is to relate a set of data that has direct bearing on the design of the system [35].

**IEEE-859 (Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities):** This standard, although focusing mainly on the reporting of

transmission *equipment* outages (as opposed to system outages), defines a major storm disaster as when the equipment design levels are exceeded, and all of the following conditions are met [36]:

- Extensive mechanical damage is evident;
- More than a specified percentage of customers have been affected;
- Service restoration takes longer than a specified time.

**Significant events (New Zealand):** TransPower defines major events as those greater than 1 system minute. These are reported in the total annual figures, but removed when describing "underlying performance". A detailed list of all such major interruptions since 1987 is published annually, together with a description of the cause of each of these [37].

A general requirement in most countries is that major events are defined in detail.

Various utilities and regulatory bodies have defined specific technical and other criteria which may be used to identify events which can be removed from the reported indices. Examples of these, primarily for distribution systems, are:

- Wind of over 80 mph [38];
- More than 1/2 inch ice loading [38];
- Earthquakes, fires, or storms of sufficient intensity to give rise to a state of emergency being declared by the government [39];
- Specific agreement between the utility and the regulatory body;
- The National Weather Service having issued a watch or warning for the area [40];
- Extensive mechanical damage [40];
- More than 10% of customers out during or immediately after the storm effects [40];
- At least 1% of the customers out after 24 hrs after the storm damage period [40].

#### ➤ **Planned and Unplanned Events**

Some utilities differentiate between planned and unplanned (forced) interruptions when reporting, while other utilities include both planned and unplanned events in a single index. This often depends on the nature of the transmission system. Utilities with more dominantly radial systems tend to differentiate the indices, whereas those with more meshed systems tend to include both in each of their indices.

**Planned interruptions** are generally defined as those where customers have been given advance notice with a corresponding minimum notice period (e.g. 2 weeks before the event).

**Unplanned interruptions** are generally defined as those which could not be avoided and where advance notice could not be provided within the required notice period. In some cases, planned interruptions which exceed the planned duration are considered as unplanned events for the excess period.

#### ➤ **Uncontrollable Events and Interruption Indices**

In some cases, the processing of events that are considered beyond a utility's control is specifically defined. Such events include riots, unrest, and third party causes. Note that lightning is not generally considered as an uncontrollable event.

**Third party events (New Zealand):** TransPower in New Zealand specifically states that all interruptions caused by third parties (generators and distribution utilities) are included in its statistics [33].

**Anomalous events (UK):** National Grid Company defines anomalous events as those events that arise as a result from particular connection or running arrangements chosen by customers, or from other causes which are not due to NGC equipment. These are however included in its annual statistics (although specifically highlighted) [28].

### 2.5.2.2 Event Duration

Where individual *customer interruptions*, or *delivery point interruptions* are considered, the duration of an event is typically the duration from when the interruption is initiated, until the supply is restored for each of these points. Where *interruption incidents* are reported, a more detailed definition is required. This may be considered as the duration from when the first *customer* or *delivery point* is interrupted, until the last *customer* or *delivery point* is restored.

#### ➤ Event Duration in the Application to Interruption Indices

The duration of an interruption event sometimes determines how it is reported. Some utilities only report events of duration longer than a given period, or report short (momentary) and long (sustained) events separately. Other utilities include all interruptions in a give index. A duration of 1 minute is common as the differentiation between momentary and sustained interruptions.

#### ➤ Phases Interrupted

Some utilities include auto-reclose events when defining interruption events (including single-phase operation). Other utilities remove these by, for example applying a 10 second minimum duration.

#### ➤ Time aggregation (single or multiple events)

The way in which consecutive multiple events due to a common cause are treated by various utilities is unclear. The manner in which this is defined will impact some indices such as number of interruptions, SAIRI and SAIFI. This needs to be defined as part of a comprehensive international recommendation.

#### ➤ Availability Indices and Interruption Indices

Availability is reduced whenever a circuit is taken out of service either for planned purposes or as a result of a fault. This does not necessarily result in an interruption to a customer. Many transmission utilities report availability indices alongside interruption indices. In some cases, availability measures reflect the level to which customer "firm" supply agreements are honored (i.e. where the supply is put at a higher risk of an interruption occurring than contracted for). Several utilities include availability indices alongside interruption indices in their performance reports (note that these transmission availability measures differ significantly from those typically used for distribution systems).

### 2.5.2.3 Other considerations

#### ➤ Reporting period

The most commonly used averaging period is one year. In some cases, a monthly reporting period is used (generally in addition to annual reporting). This highlights seasonal effects - such as performance during system peak loading periods [28].

#### ➤ Delivery and Reception Points

In the past, due to the vertically integrated nature of most utilities, transmission interruption indices have generally focused only on delivery points. Recent Cigre Study Committee 39 recommendations have included reception points (generators and interconnections) in transmission interruption indices

such as SAIDI, SAIFI, and SAIRI. The aim is to better define the indices for application to transmission systems in liberalized electricity markets (i.e. providing services to both generators and their customers) [30].

➤ **System size definition for averaged severity indices**

A particular concern in averaged severity indices is the description of the size of the system, i.e. is this based on:

- The system total annual energy demand,
- the system peak power demand to date;
- the system peak demand for the period reported;
- or the system peak demand for the previous year.

The latter, although offset by a year, simplifies monthly reporting within a utility where the peak demand does not correspond with the reporting period (e.g. reporting January to December where the peak occurs in July would result in a discontinuity in the reported figure in July if the system peak demand to date was used)

Other definition requirements that are not clear in the application of severity indices are whether:

- system losses are included or not;
- how interconnections are treated (these may in the case of net export increase the system peak).

### 3 REVIEW OF MEASUREMENT DATA

An important part of the working group activities was the collection of measurement data. The working group did not perform any measurements itself but collected survey results from past or ongoing surveys.

In order to address the confidentiality concerns from organizations who provided measurement results, it was decided that the measurement data will be reported in an anonymous manner, except for cases where reference is made to already published material.

The following is a summary of the measurement results available and the reader is invited to refer to annex B for more details on measurement results for each survey.

#### 3.1 HARMONICS

##### 3.1.1 SUMMARY OF THE RESULTS

The gathering of harmonic measurement data revealed disparities among the surveys in terms of measurement methods (e.g. in some cases 1-min integration time instead of 10-min), measurements for less than one week, different indices (average value or 95%-site). To handle consistent data, some assumptions were made (1-minute values will be considered as a short time and 5-seconds as a very short time) and all the survey results for harmonics were filtered according to the **following criteria**:

- harmonic measurements made using capacitive voltage transformers are not considered;
- only harmonic surveys consisting of 10 sites or more for at least one week duration are reported.

| Survey | Index and statistical parameters  | Harmonic orders    | Voltage levels | Number of sites | Duration each site    | Comply criteria |
|--------|---|--------------------|----------------|-----------------|-----------------------|-----------------|
| H-1    | MV: $U_{h,sh95} + U_{h,sh99}$ both for all-sites and 95%-site<br>HV: $U_{h,vs95} + U_{h,vs99} + U_{h,sh95} + U_{h,sh99}$ for all-sites and 95%-site | 2 – 45, THD        | MV             | 118             | 1 week                | Yes             |
|        |   |                    | HV             | 32              | 3-6 months            | Yes             |
|        |   |                    | EHV            | 3               | 3-6 months            | No              |
| H-2    | $U_{h,sh95} + U_{h,sh99}$ for all-sites and 95%-site  | 2 – 45, THD        | HV             | 43              | 1 week                | Yes             |
|        |   |                    | EHV            | 205             | 1 week                | Yes             |
| H-3    | $U_{h,sh95}$  | 2 – 25, THD        | MV             | 7               | 20 months             | No              |
|        |   |                    | HV             | 4               |                       | No              |
|        |   |                    | EHV            | 1               |                       | No              |
| H-4    | $U_{h,vsmax}$   | 2 – 45, THD        | MV             | 28              | Few hours to few days | No              |
|        |   |                    | HV             | 14              |                       | No              |
| H-5    | $U_{h,vs95}$  | 2 – 13, THD        | MV             | 5               | 1 day                 | No              |
| H-6    | $U_{h,shmax}$   | 5, THD             | HV, EHV        | 59              | 5 days                | No              |
| H-7    | $U_{h,vs95} + U_{h,sh95} + U_{h,vsmax} + U_{h,shmax}$ for all-sites and 95%-site  | 1 – 50, THD        | HV             | 10              | 3 years               | Yes             |
| H-8    | $U_{h,sh95} + U_{h,shmax}$ for all-sites and 95%-site.  | 3, 5, 7, 11        | MV             | 60              | 1 week                | Yes             |
|        |   |                    | HV             | 60              | 1 week                | Yes             |
|        |   |                    | EHV            | 12              | 1 week                | Yes             |
| H-9    | $U_{h,sh95}$ for all-sites and 95%-site   | 2, 3, 5, 7, 9, THD | HV             | 21              | 1 week                | Yes             |
| H-10   | $U_{h,sh95}$ for all-sites and 95%-site   | 2, 3, 5, 7, THD    | HV             | 64              | 2 years               | Yes             |
|        |   |                    | EHV            | 3               | 2 years               | No              |
| H-11   | $U_{h,sh95}$ for all-sites and 95%-site   | 3, 5, 7, 9, 11     | HV             | 54              | 3 years               | Yes             |
| H-12   | $U_{h,sh95}, U_{h,sh99}$  | 2 – 45, THD        | MV             | 2               | 1 – 2 weeks           | No              |

Table 15: Summary of general parameters for harmonic surveys.

Table 15 shows for each survey the statistical parameters, the harmonic orders, the number of sites and duration, and it shows which survey actually meet the criteria.

Where:

- $U_{h,vs95}$ : the greatest 95% probability daily value of  $U_{h,vs}$  (vs: 3-sec rms values);
- $U_{h,vs99}$ : the greatest 99% probability daily value of  $U_{h,vs}$ ;
- $U_{h,vsmax}$ : the maximum daily value of  $U_{h,vs}$ ;
- $U_{h,sh95}$ : the greatest 95% probability weekly value of  $U_{h,sh}$  (sh:10-min rms values);
- $U_{h,sh99}$ : the greatest 99% probability weekly value of  $U_{h,sh}$ ;
- $U_{h,shmax}$ : the maximum weekly value of  $U_{h,sh}$ .

A comparative analysis of measurement results that comply with the above mentioned criteria consists of:

- 2 harmonic surveys for **MV** systems totaling **178** measurement sites;
- 7 harmonic surveys for **HV** systems totaling **284** measurement sites;
- 2 harmonic surveys for **EHV** systems totaling **217** measurement sites.

Analysis of the results shows that the basic statistical parameter for comparing the data is the  $U_{h,sh95}$  for maximum site and 95%-site because values for this index were available for all valid surveys.

In order to compare measurement results with planning levels in IEC 61000-3-6, a global average consisting of the mean value of harmonic voltages among the available surveys is shown on the graphs next (the worst survey result may not be representative, and a “95%-survey” value would not be relevant because of the number of surveys available). However for completeness, tables showing minimum and maximum along with the mean values among surveys are also given below for dominant harmonic orders.

### 3.1.1.1 MV Measurement results

All detailed measurement results are shown in Annex B. A summary of the measurement results for MV (1 to 35 kV) complying with criteria above is shown on Figure 4.

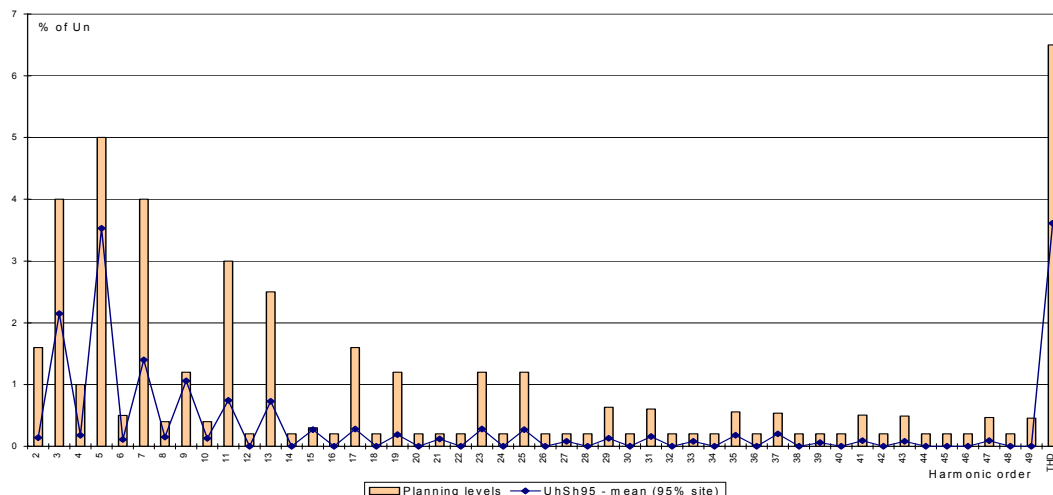


Figure 4: Mean value among surveys of the 95%-site of  $U_{h,sh95}$  versus planning levels given in IEC 61000-3-6 for MV systems.

At MV, only 2 valid surveys (totaling 178 sites) met the criteria. The dispersion of the values for some harmonic orders is given in Table 16 in comparison to planning levels.

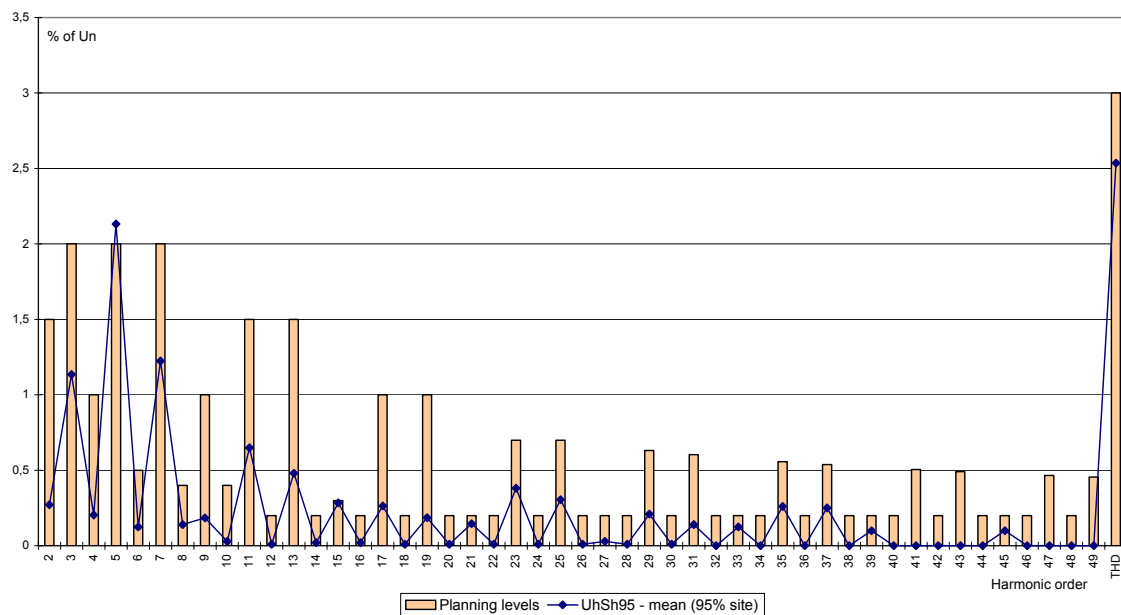
| Harmonic order | Measurement results<br>95%-site for $U_{h,sh95}$ |      |      | Measurement results<br>max-site for $U_{h,sh95}$ |     |      | Planning levels |
|----------------|--|------|------|--|-----|------|-----------------|
|                | Min  | Max  | Mean | Min  | Max | Mean |                 |
| 3              | 1,5  | 2,8  | 2,15 | 2  | 3,7 | 2,85 | 4               |
| 5              | 2,56   | 4,5  | 3,53 | 4,2  | 5   | 4,6  | 5               |
| 7              | 1,3  | 1,5  | 1,4  | 1,5  | 3,4 | 2,4  | 4               |
| 11             | 0,5  | 0,95 | 0,75 | 1  | 3,8 | 2,4  | 3               |

**Table 16: Dispersion of results among surveys for some harmonic orders at MV.**

At 5<sup>th</sup> harmonic, the measured values are 2,56% and 4,5% for the only two available surveys. In this case, the use of the mean value among the available results could be questioned because conclusions will be very different from one survey to another due to limited data available. However, it is interesting to note that the mean value of 3,53% at 5<sup>th</sup> harmonic shown above can be compared with a number of results given in a recent Eurelectric report concerning power quality measurements results in Europe [42].

### 3.1.1.2 HV Measurement results

A summary of the measurement results at HV (35 to 230 kV) complying with the criteria is shown on figure below.



**Figure 5: Mean value among surveys of the 95%-site of  $U_{h,sh95}$  versus planning levels of IEC 61000-3-6 for HV systems.**

At HV (7 valid measurement surveys totaling 284 sites), it can be observed that the planning levels are exceeded for some harmonic orders such as 5, 15 considering the mean value of 95%-site among different surveys. For the 5<sup>th</sup> harmonic, dispersion of the measured values among the different surveys range between 1% and 3%, as shown in the Table 17 (see also **Figure 7** for more details):

| Harmonic order | Measurement results<br>95%-site for $U_{h,sh95}$ |      |      | Measurement results<br>max-site for $U_{h,sh95}$ |      |      | Planning levels |
|----------------|--|------|------|--|------|------|-----------------|
|                | Min  | Max  | Mean | Min  | Max  | Mean |                 |
| 3              | 0,62   | 1,51 | 1,13 | 1  | 2,51 | 1,5  | 2               |
| 5              | 1,0  | 3    | 2,13 | 1  | 3,2  | 2,5  | 2               |
| 7              | 0,4  | 2,14 | 1,22 | 0,4  | 2,4  | 1,3  | 2               |
| 11             | 0,48   | 1,24 | 0,64 | 0,5  | 1,5  | 0,78 | 1,5             |

Table 17: Dispersion of results among surveys for some harmonic orders at HV.

### 3.1.1.3 EHV Measurement results

A summary of the measurement results at EHV (over 230 kV) complying with the criteria is shown on Figure 6.

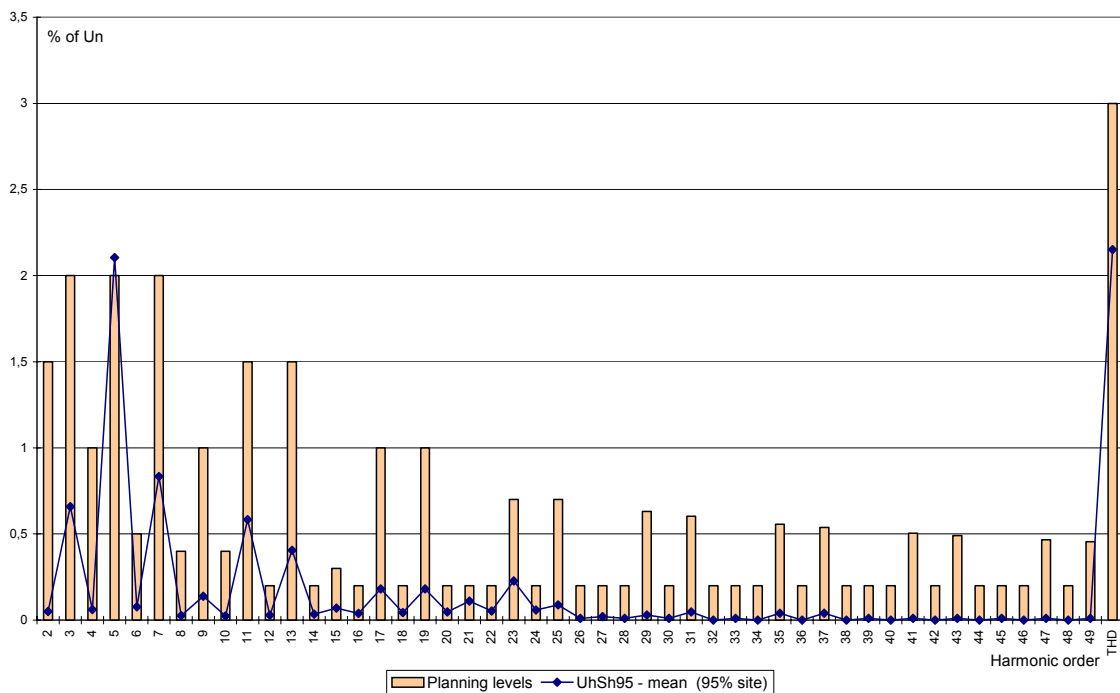


Figure 6: Mean value among surveys of the 95%-site of  $U_{h,sh95}$  versus planning levels of IEC 61000-3-6 for EHV systems.

At EHV (2 valid surveys totaling 217 sites), it can be observed that only the planning levels for harmonic 5 is exceeded. For this harmonic order, dispersion of the measured values among the different surveys range between 1,8% to 2,4%, as indicated in the following table:

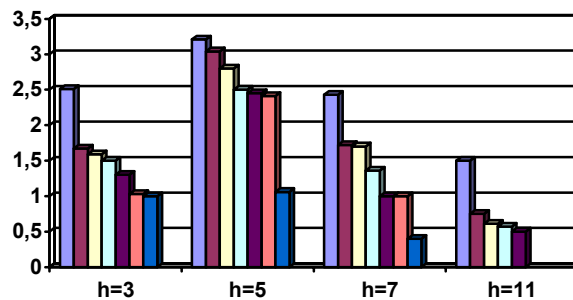
| Harmonic order | Measurement results<br>95%-site for $U_{h,sh95}$ |      |      | Measurement results<br>max-site for $U_{h,sh95}$ |      |      | Planning levels |
|----------------|--|------|------|--|------|------|-----------------|
|                | Min  | Max  | Mean | Min  | Max  | Mean |                 |
| 3              | 0,6  | 0,71 | 0,65 | 0,6  | 1,4  | 1    | 2               |
| 5              | 1,81   | 2,4  | 2,1  | 2,51   | 3    | 2,75 | 2               |
| 7              | 0,66   | 1    | 0,83 | 1  | 1    | 1    | 2               |
| 11             | 0,56   | 0,6  | 0,58 | 0,6  | 0,71 | 0,65 | 1,5             |

Table 18: Dispersion of results among surveys for some harmonic orders for EHV.

### 3.1.2 CONCLUSIONS REGARDING HARMONIC MEASUREMENT RESULTS

The results show that the “very-short time” 3-sec rms indices as proposed in IEC 61000-3-6 are generally not available (available for only 2 surveys at HV totaling only 42 sites) for comparison with planning levels especially at MV and EHV.

The most common index available is the 95% 10-min value ( $U_{h,sh95}$ ) for the maximum site and 95%-site. From the available measurement results at HV (7 measurement surveys complying with the chosen criteria and totalling some 284 sites), it is obvious that the planning levels for HV systems are exceeded in many cases, especially at 5<sup>th</sup> harmonic, because of the generally higher measured levels and the relative consistency of results between the different surveys (5<sup>th</sup> harmonic often between 2,4 and 3,2% compared to a planning level of 2%) as can be seen on the Figure 7.



**Figure 7: Low order harmonic voltages (ordinate in %) from 7 different surveys at HV for  $U_{h,sh 95}$  considering all sites (284 sites).**

At MV and EHV however it is more difficult to draw similar conclusions because, although there are measurement results from nearly 200 sites, each meeting the criteria, the available results come from only two different surveys.

## 3.2 FLICKER

### 3.2.1 SUMMARY OF THE RESULTS

In contrast to harmonics, it was not possible to gather flicker measurement results for the 95%-site or the 99%-site in each survey, but detailed results were available for each monitored site individually. The reason is basically that flicker measurements are conducted at fewer sites and there is less data available compared to the situation with individual harmonics. Table 19 summarises the available data of which details are given in annex B. Figure 8 to Figure 11, on the next pages, show all the available results for the 95% and 99% percentiles of  $P_{st}$  and  $P_{lt}$  indices.

| Survey  | Index and statistical parameters   | Duration          | Voltage levels | Number of sites |
|---------|--|-------------------|----------------|-----------------|
| F-1-5   | $P_{st\ 95}$ , $P_{lt\ 95}$  | 2-3 wk.           | MV, HV         | 5               |
| F-6-7   | $P_{st\ 95}$ , $P_{st\ 99}$  | -                 | HV, EHV        | 6               |
| F-8     | $P_{st\ 95}$ , $P_{st\ 99}$ and $P_{st\ max}$  | 1 month           | MV, HV<br>EHV  | 7               |
| F-9-11  | $P_{lt\ 95}$   | 3 wk. to 1 yr.    | HV, EHV        | 18              |
| F-12    | $P_{st\ 95}$ , $P_{st\ 99}$ and $P_{lt\ 95}$ , $P_{lt\ 99}$  | 1 wk.             | MV             | 112             |
| F-13    | $P_{st\ 95}$ , $P_{st\ 99}$ and $P_{lt\ 95}$ , $P_{lt\ 99}$  | 3 wk. to 6 months | HV             | 12              |
| F-14    | $P_{lt\ 95}$ , $P_{lt\ 99}$ and $P_{lt\ max}$ and $P_{st\ 95}$ , $P_{st\ 99}$ and $P_{st\ max}$ for 1 site | 8 days            | HV, EHV        | 6               |
| F-15-16 | $P_{st\ 95}$ , $P_{st\ 99}$  | 3 - 8 days        | HV             | 2               |
| F-17    | $P_{st\ 95}$   | 1 wk.             | HV, EHV        | 41              |
| F-18    | Comparison of statistical data   | 1 wk.             | LV to EHV      | 37              |
| F-19    | $P_{lt\ 95}$ , $P_{lt\ 99}$ daily and weekly profiles over 2,5 years                                       | 2,5 years         | EHV            | 1               |

Table 19: Summary of general parameters for flicker surveys.

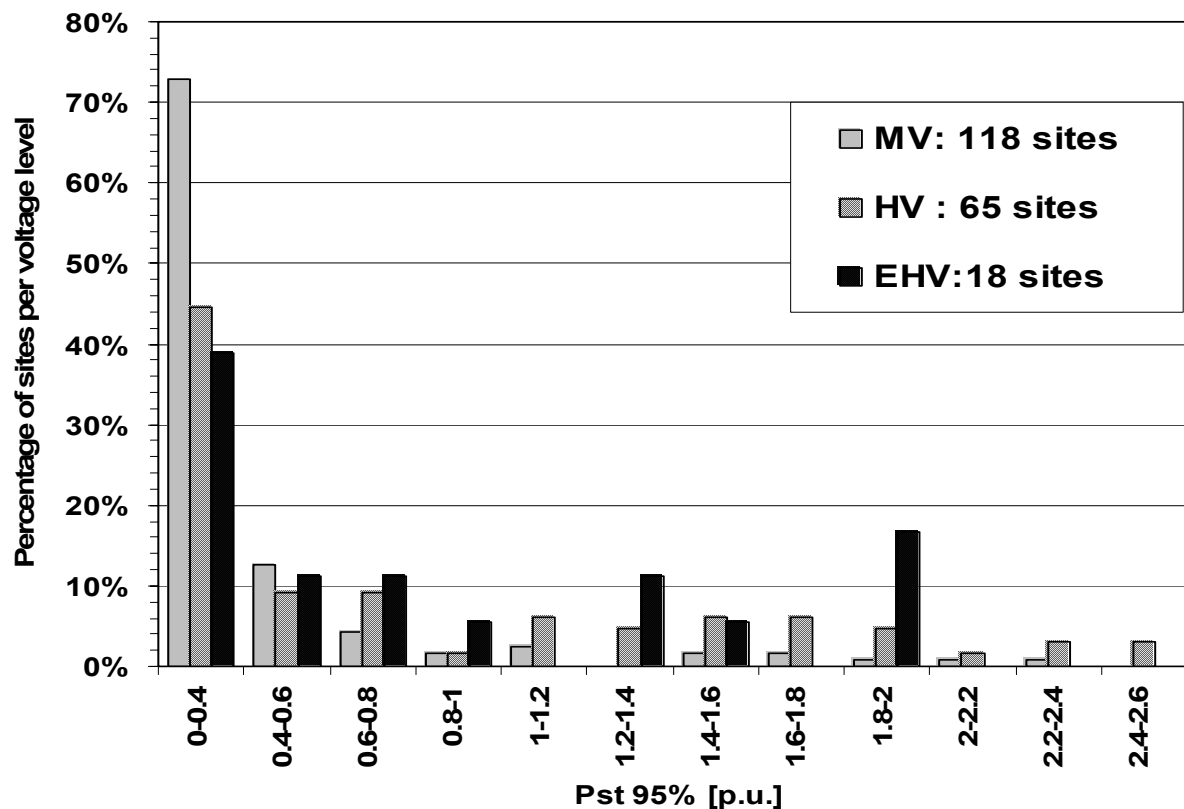


Figure 8: Measurement data for flicker  $P_{st\ 95}$  at MV, HV and EHV – all sites.

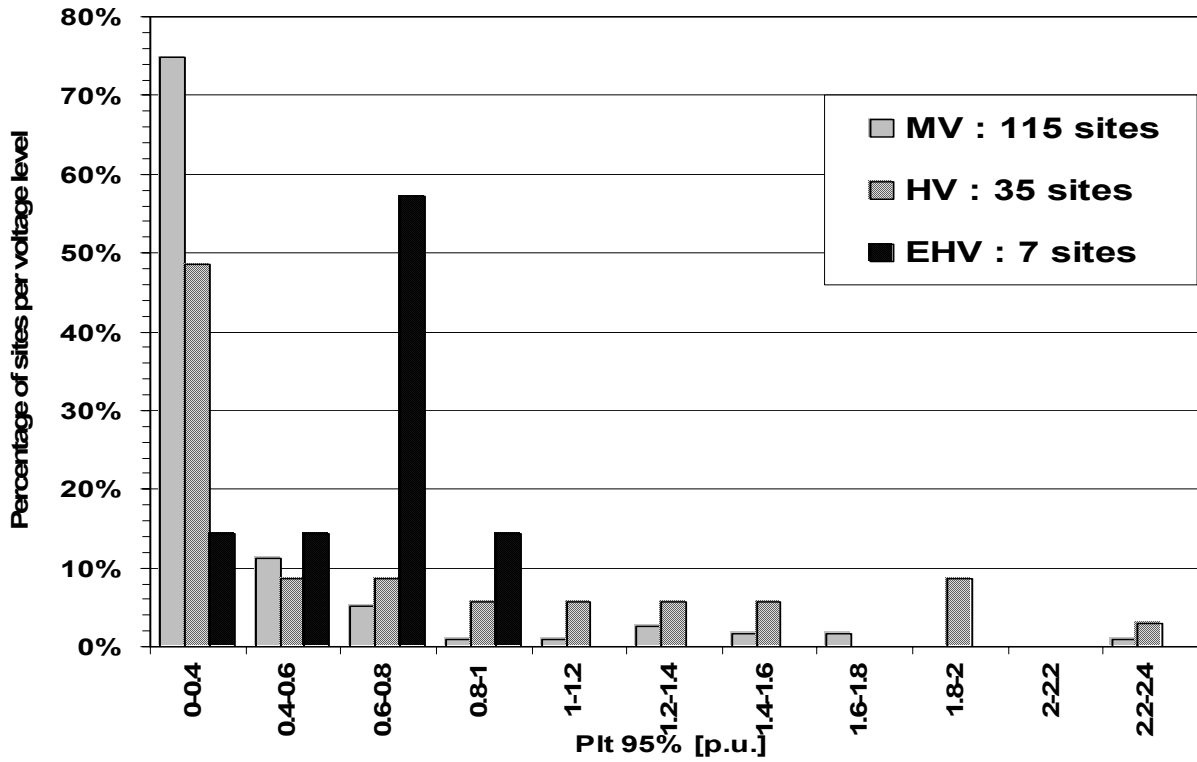


Figure 9: Measurement data for flicker P<sub>It 95%</sub> at MV, HV and EHV – all sites.

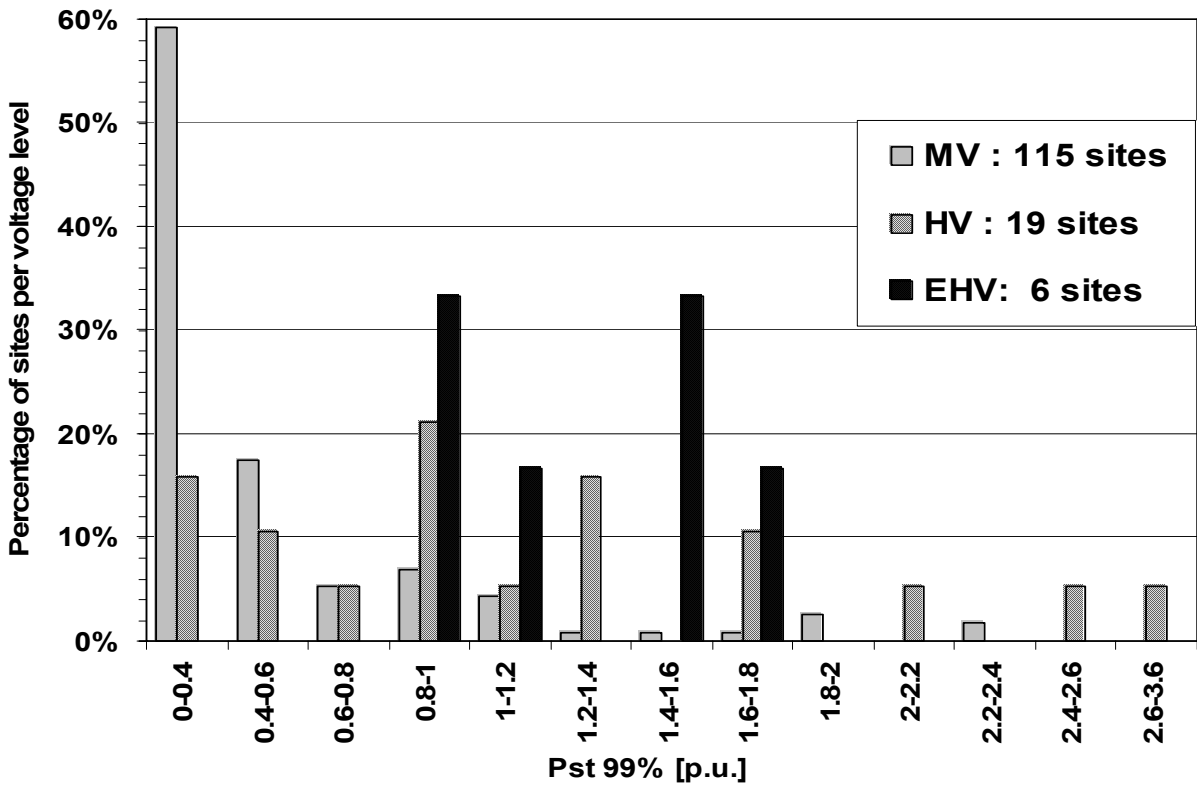


Figure 10: Measurement data for flicker P<sub>st 99%</sub> at MV, HV and EHV – all sites.

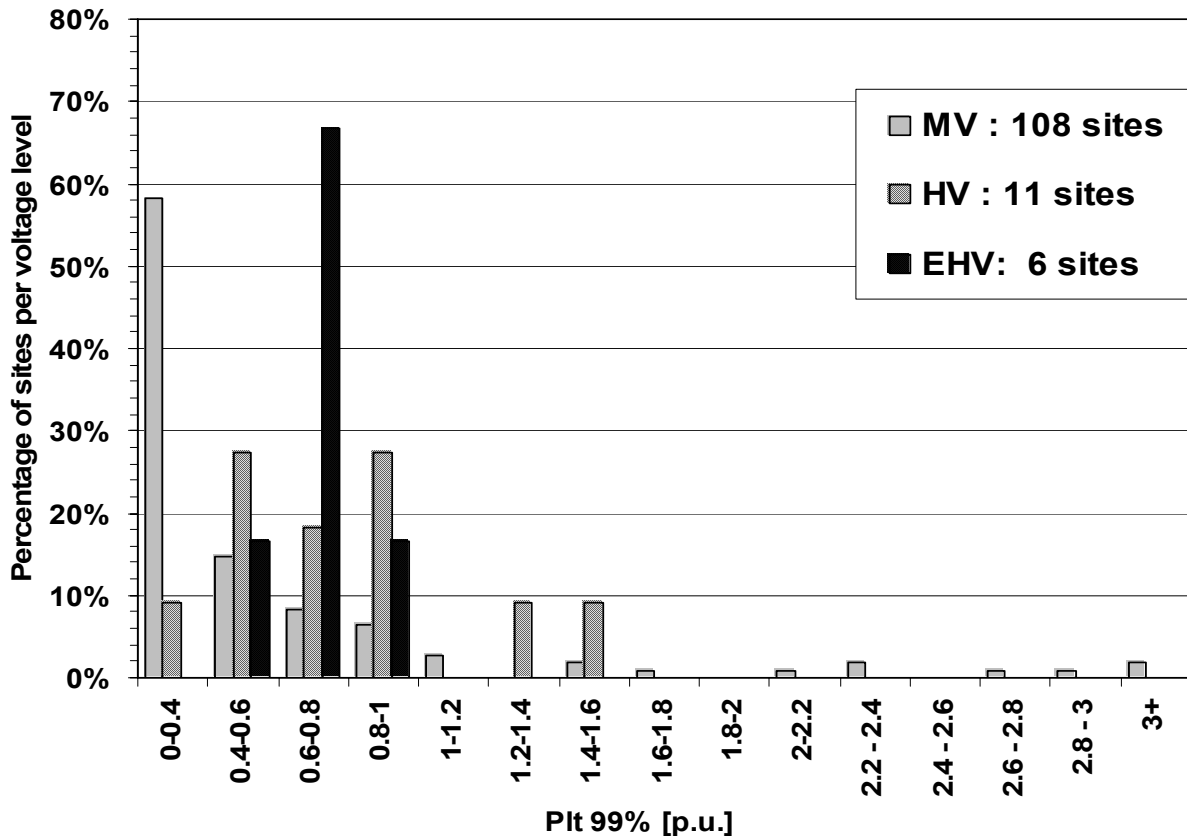


Figure 11: Measurement data for flicker  $P_{lit 99}$  at MV, HV and EHV – all sites.

### 3.2.2 CONCLUSIONS REGARDING FLICKER MEASUREMENT RESULTS

- Measurements are often conducted in the vicinity of important flicker sources for characterising the worst network locations in view of the need to comply with Standards such as EN 50160. These measurements show high values for the flicker severity (often higher than the severity limits defined in the standards).
- Available statistical parameters are very few, particularly for EHV. The measurement data are often given only for statistical parameters, for example 95 percentile over time or the maximum value. These values cannot be directly compared with the 99% indices for planning levels proposed in [2].
- However, the measurement results shows evidence of the actual difficulties in respecting the planning levels proposed in [2] at many of the recorded worst locations. In many countries, with strong and meshed networks, the actual flicker disturbance is sometimes more than double the planning levels without known problems.
- Influential parameters such as type of lighting equipment in use, time of the day or night, flicker transfer/attenuation factor between different voltage levels, etc., also need to be considered for interpreting results.

#### 3.2.2.1 Considerations about the flicker phenomenon

In view of the relatively high measured flicker levels compared to the standard limits, it may be worthwhile to recall some fundamentals of the flicker phenomenon as this should provide indications for an eventual revision of the limits:

- voltage fluctuations that produce flicker are in the order of few percent or less and in practice do not disturb sensitive equipment/process;
- the only effect of flicker is limited to the visual discomfort induced by light stimulus whose luminance or spectral distribution fluctuates with time;
- perception of flicker depends on the physiology of the eye-brain of the person subjected to the luminance fluctuation. That is to say the flicker is a subjective perception;
- flicker was originally related to the behaviour of a specific incandescent lamp (230 V, 60 W) when subjected to voltage fluctuation. The level of flickering in new lamps varies from this specific basis;
- to this end, some recent tests about new types of lamps versus flicker are given in reference [43]. A significant contribution in defining flicker-performance of modern lightning technologies has been given by EPRI's Power Electronics Applications Center and Canadian Electrical Association that performed flicker tests on several types of modern lighting. During these tests the lamp's amplifying characteristic, or gain factor, was analyzed. If the percentage of relative light fluctuation is greater than the percentage of voltage fluctuation, the lamp is said to have a gain factor greater than unity. The following Figure 12 reproduced from ref. [43] shows an example of measured gain factors for different types of lamps over the range of frequency which causes flicker. It can be observed that some fluorescent lamps with an electronic ballast may be 5 times less likely to produce flicker compared to incandescent lamps (gain factor of 0,5 compared to 2,5 for the critical flicker frequency at 10 Hz).

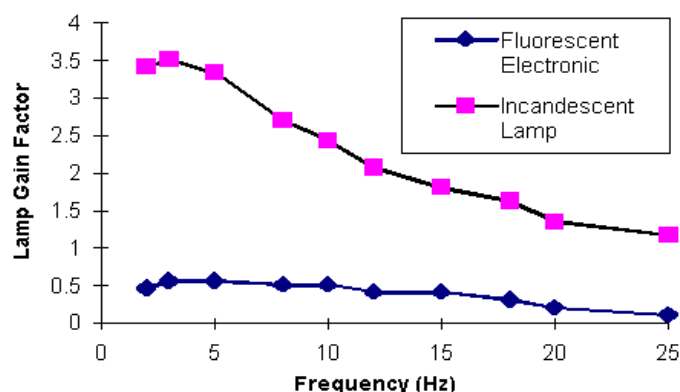


Figure 12: Lamp Gain versus Flicker Frequency for Fluorescent Electronic and Incandescent lamps.

### 3.3 UNBALANCE

#### 3.3.1 SUMMARY OF THE RESULTS

Table 20 summarizes the available data and more details can be found in annex B.

The available statistical data covers 99 sites at MV, 76 sites at HV and 25 sites at EHV. Figure 13 shows the most commonly available index for voltage unbalance averaged over short 10 min periods: the 95 percentile over time for a weekly statistics (the number of sites versus Voltage Unbalance Factor -  $U_{neg}$  in %).

| Survey | Index and statistical parameters  | Duration    | Voltage levels | Number of sites |
|--------|---|-------------|----------------|-----------------|
| U-1    | $U_{neg,sh95}$  | 20 mths     | MV             | 7               |
|        | $U_{neg,sh95}$  | " "         | HV             | 4               |
|        | $U_{neg,sh95}$  | " "         | EHV            | 1               |
| U-2-3  | $U_{neg,sh95}$ (in this case sh = 5 min)  | 1 wk        | HV             | 62              |
| U-4    | $U_{neg,sh95}$ ; $U_{neg,sh99}$   | 3-6 mths    | HV             | 28              |
|        | $U_{neg,lt95}$ ; $U_{neg,lt99}$   | 3-6 mths    | HV             | 11              |
| U-5    | $U_{neg,sh95}$ ; $U_{neg,sh99}$   | 3-6 mths    | EHV            | 13              |
| U-6    | $U_{neg,sh95}$ ; $U_{neg,sh99}$ ; $U_{neg,lt95}$ ; $U_{neg,lt99}$                         | 1 wk        | MV             | 92              |
| U-7    | $U_{neg,sh95}$  | 1 year      | HV             | 2               |
| U-8    | $U_{neg,sh95}$  | $\geq 1$ wk | HV             | 8               |
| U-9    | $U_{neg,sh95}$  | 1 wk        | HV             | 1               |
|        | $U_{neg,sh95}$  | 3 wks       | EHV            | 1               |
| U-10   | $U_{neg,vs95}$ ; $U_{neg,vs99}$ ; $U_{neg,vsmax}$<br>3-sec values profiles over one year. | 1 year      | HV             | 1               |

Table 20: Summary of general parameters for voltage unbalance surveys.

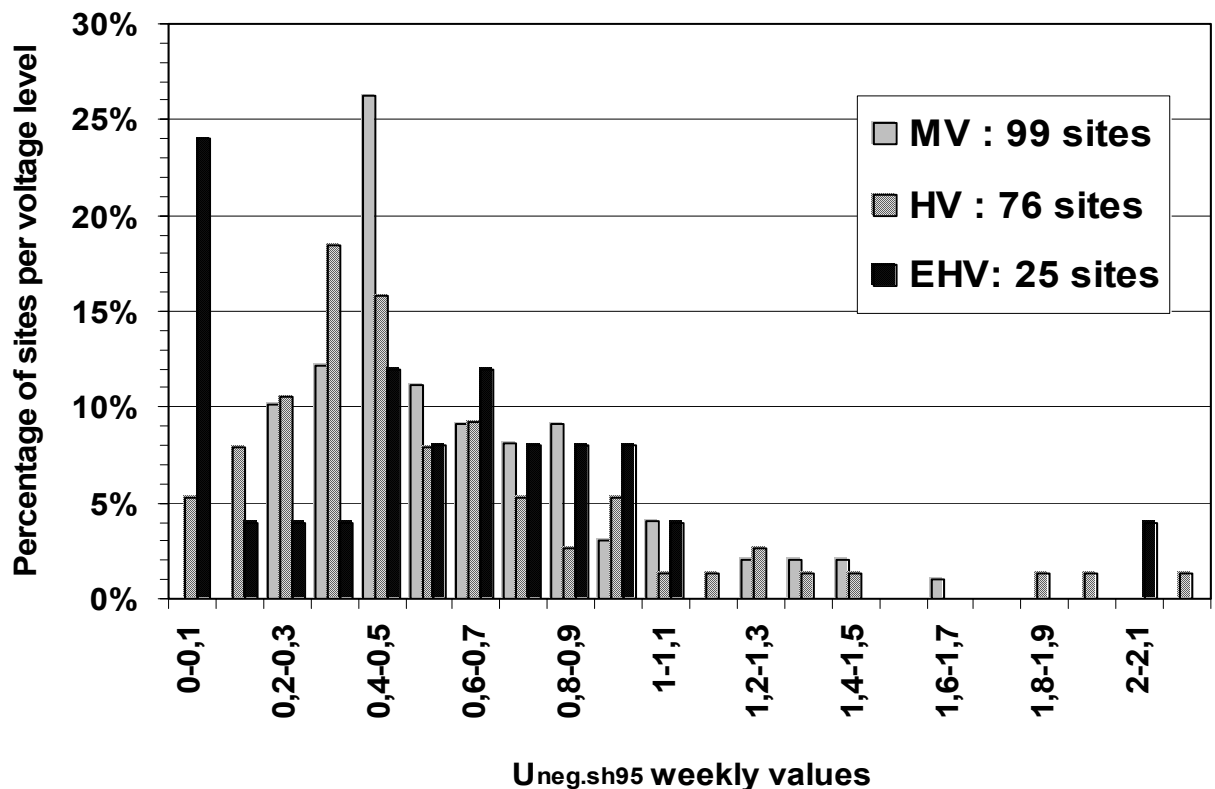


Figure 13: Measurement data for voltage unbalance at MV, HV and EHV – all sites.

The gathering of voltage unbalance measurement data revealed that:

- Different survey durations are reported for measurement, however results, in most cases, are given for weekly statistics;
- For some surveys, statistical parameters for 99% over time are also available (see Annex B for more details).

### 3.3.2 CONCLUSIONS REGARDING VOLTAGE UNBALANCE MEASUREMENT RESULTS

Here too, system-wide unbalance surveys and routine measurements are uncommon and the available statistical parameters are limited. At MV, 92 of the 99 sites reported were obtained from the results of just one measurement survey. Nevertheless, in view of the voltage characteristics and some national recommendations, the following conclusions regarding measurement results are:

- **none** of the reported **MV** sites exceed **2%**;
- for **HV** sites, more than **11,8%** of sites (9 out of 76) reach or exceed **1%** voltage unbalance, while **less than 4 % of sites** (3 out of 76) **exceed 1,5%** voltage unbalance;
- at **EHV**, **very few sites** (1 out of 25) show voltage unbalance exceeding **1,1%**.

Although limited, the above measurement results provide useful indications on voltage unbalance for setting future planning levels and voltage characteristics in HV and EHV systems.

## 3.4 VOLTAGE DIPS

### 3.4.1 ANALYSIS OF THE RESULTS

Due to limited statistical results available here, the definition of voltage range slightly differs from the previous one in that “MV” includes up to 36 kV.

#### 3.4.1.1 Overview of available data

| System voltage | Survey | Monitor-years | Voltage level(s)  | Non-available data   |
|----------------|--------|---------------|-------------------|--|
| MV             | D-1    | 120           | 13 - 26kV         |  |
|                | D-2    | 67            | 10 - 16.5kV       |  |
|                | D-3    | 80            | 30kV, 36kV        |  |
|                | D-4    | 45            | 20kV              | Non-UNIPED format  |
| HV             | D-5    | 150           | 66kV, 77kV, 154kV | Monitoring period only three months;<br>Only average values available<br>Non-UNIPED format |
|                | D-6    | 110           | 70kV              |  |
|                | D-7    | 114           | 150kV             |  |
|                | D-9    | n.a.          | 110kV             | Non- UNIPED format<br>Stochastic prediction of dip statistics                              |
|                | D-10   | 126           | 132 kV            |  |
|                | D-11   | 59            | 88 kV             |  |
| EHV            | D-12   | 24            | 380kV             |  |
|                | D-13   | 6             | 400kV             |  |
|                | D-14   | 100           | 400 kV            | monitoring takes place continuously, no information on monitoring duration available       |
|                | D-15   | 9             | 275 kV            |  |

**Table 21: Overview of Surveys and Data Availability for dips.**

An overview of the voltage-dip surveys is given in Table 21. A summary of the results is presented below. The results are presented in detail in Annex B, including information on the monitor settings and the system configuration. When interpreting the results below it should be noted that for most surveys the monitors were connected in star (i.e. phase to neutral) configuration. The monitors were connected in delta (i.e. phase to phase) configuration for survey D-4 and for some locations of survey D-2. A lower dip frequency is expected for delta-connected monitors, especially in high-impedance earthed systems.

### 3.4.1.2 Comparison of MV Survey Data

Three MV surveys (D-1, D-2 and D-3) are compared in Table 22: the three values in each cell of the table give the voltage-dip frequency for the three surveys. The results for survey D-4 are presented in a different table so that a cell-by-cell comparison is not possible. The three surveys show a large variation in voltage-dip frequency. It is difficult to find a representative value covering all three networks. The 50-% sites are compared in Table 23 which again shows a large variation in voltage-dip frequencies. The SARFI-index values for the three surveys are given in Table 24, where the 50-% index is used for surveys D-2 and D-4, instead of the average over the sites; the average over all the sites was not available for those surveys. For survey D-3 the SARFI values were calculated both for the average of all sites and for the 50% site. The average gives a higher value because it is dominated by a small number of sites with a very high dip frequency.

| Retained voltage | <20ms   | 20-100ms     | 0.1-0.5s     | 0.5-1s    | 1-3s      | 3-20s   | 20-60s  | 60-180s |
|------------------|---------|--------------|--------------|-----------|-----------|---------|---------|---------|
| 85-90%           | 0-0-0.8 | 150-16.7-4.8 | 37-9.0-2.6   | 9-2.7-1.2 | 6-0.7-0.3 | 3-0-0   | 2-0-0   | 1-0-0   |
| 70-85%           |         | 238-13.0-3.6 | 93-29.1-2.4  | 14-7-1.0  | 5-1.7-0.3 | 1-0-0   |         |         |
| 40-70%           |         | 141-8-1.0    | 128-17.9-1.0 | 15-7-0.2  | 5-1-0.2   | 1-0-0   |         |         |
| 10-40%           |         | 55-1.7-1.8   | 113-6.7-1.5  | 12-1-0    | 4-1.7-0   | 1-0-0   |         |         |
| <10%             |         | 0-0-0.3      | 4-1-2.2      | 1-1-0.3   | 6-1-0     | 7-1-0.3 | 2-0-0.3 | 3-1-0.2 |

Table 22: Comparison of MV Surveys, number of events per year, 95%-sites.

| Retained voltage | <20ms   | 20-100ms   | 0.1-0.5s   | 0.5-1s  | 1-3s    | 3-20s   | 20-60s  | 60-180s |
|------------------|---------|------------|------------|---------|---------|---------|---------|---------|
| 85-90%           | 0-0-0.2 | 47.1-4-2   | 11.7-2-0.4 | 2.3-0-0 | 1.2-0-0 | 1.5-0-0 | 1.1-0-0 | 0.2-0-0 |
| 70-85%           |         | 63.9-4-2   | 28.1-4-1.2 | 5.3-0-0 | 1.0-0-0 | 0.2-0-0 |         |         |
| 40-70%           |         | 36.5-1-0.2 | 31.9-2-0.3 | 3.6-0-0 | 1.1-0-0 | 0.2-0-0 |         |         |
| 10-40%           |         | 10.4-0-0.3 | 24.2-0-0.3 | 2.5-0-0 | 0.8-0-0 | 0.2-0-0 |         |         |
| <10%             |         |            | 0.8-0-0.3  | 0.3-0-0 | 1.1-0-0 | 1.4-0-0 | 0.4-0-0 | 0.6-0-0 |

Table 23: Comparison of MV Surveys, number of events per year, 50%-sites.

| SARFI-Index     | Survey D-1 | Survey D-2 | Survey D-3 |        | Survey D-4 |
|-----------------|------------|------------|------------|--------|------------|
|                 | (mean)     | (50%)      | (50%)      | (mean) | (50%)      |
| <b>SARFI_90</b> | 279.6      | 17         | 7.2        | 11.3   | 181        |
| <b>SARFI_85</b> | 214.5      | 11         | 4.6        | 7.2    | n.a.       |
| <b>SARFI_70</b> | 116.0      | 3          | 1.4        | 3.4    | 106        |
| <b>SARFI_40</b> | 42.7       | 0          | 0.9        | 2.5    | 56         |
| <b>SARFI_10</b> | 4.6        | 0          | 0.3        | 1.4    | 40         |

Table 24: Comparison of MV Surveys, SARFI-values, number of events per year.

The effect of time-aggregation on the 50 percentile and 95 percentile tables for MV Survey D-3 is summarized in Table 25.

| Retained voltage range | 95-percentile values |        |        | 50-percentile values |        |        |
|------------------------|----------------------|--------|--------|----------------------|--------|--------|
|                        | none                 | 10-sec | 10-min | none                 | 10-sec | 10-min |
| 85-90%                 | 9.7                  | 9.1    | 8.9    | 2.6                  | 2.2    | 2.2    |
| 70-85%                 | 7.3                  | 7.0    | 6.8    | 3.2                  | 3.0    | 3.0    |
| 40-70%                 | 2.4                  | 2.4    | 2.1    | 0.5                  | 0.5    | 0.5    |
| 10-40%                 | 3.3                  | 3.0    | 2.1    | 0.5                  | 0.5    | 0.5    |
| 0-10%                  | 3.6                  | 3.6    | 3.6    | 0.3                  | 0.3    | 0.3    |

Table 25: Effect of time aggregation on the indices for MV survey D-3.

### 3.4.1.3 Comparison of HV Survey Data

The HV data is incompatible in two aspects. The results for survey D-5 and Survey D-9 are given in a different format; the results for survey D-9 are obtained through stochastic prediction instead of through monitoring. It was decided to translate the results from surveys D-5 and D-9 into the UNIPED-format through interpolation [52].

A comparison of the voltage-dip frequencies is shown in Table 26. There are obvious differences between the different systems, but not as pronounced as with distribution networks. The SARFI values are compared in Table 27. For most surveys only the SARFI value is given for the 50%-site as no other information was available. For surveys D-6 and D-7 also the SARFI value for the average of all sites is given. The value for the 50% site is in cases lower than for the average site.

| Retained voltage | 20-100ms            | 0.1-0.5s            | 0.5-1s          | 1-3s            |
|------------------|---------------------|---------------------|-----------------|-----------------|
| 85-90%           | 1.4-5.6-3.4-0-22-26 | 1.6-2.6-0.6-8-4-4   | 0.1-0.2-0-4-1-1 | 0.2-0-0-0-0-0-0 |
| 70-85%           | 2.1-4.3-4.0-0-45-41 | 2.1-4.3-1.3-10-9-11 | 0.1-0.2-0-4-3-3 | 0.3-0-0-0-0-1   |
| 40-70%           | 1.2-1.2-1.6-0-16-15 | 1.3-2.0-0.6-2.7-4-5 | 0.1-0-0-0-1-1   | 0.2-0-0-0-0-0   |
| 10-40%           | 0.5-0.5-0.2-0-2-1   | 0.6-0.7-2-0.3-1-1   | 0.1-0-0-0-0-0   | 0.2-0-0-0-0-0   |
| <10%             |                     |                     |                 |                 |

Table 26: Comparison of HV Surveys, number of events per year, 50%-sites.

| SARFI-Index | D-5   | D-6    |       | D-7    |       | D-9   | D-10  | D-11  |
|-------------|-------|--------|-------|--------|-------|-------|-------|-------|
|             | (50%) | (mean) | (50%) | (mean) | (50%) | (50%) | (50%) | (50%) |
| SARFI_90    | 12.1  | 32.7   | 22.2  | 17.4   | 12.1  | 29.0  | 109   | 110   |
| SARFI_85    | 8.8   | 20.8   | 13.2  | 12.7   | 7.9   | 17.0  | 81    | 79    |
| SARFI_70    | 4.2   | 8.6    | 4.4   | 4.2    | 2.6   | 3.0   | 24    | 23    |
| SARFI_40    | 1.4   | 3.1    | 1.2   | 1.5    | 0.4   | 0.3   | 3     | 2     |
| SARFI_10    |       | 1.3    | 0.0   | 1.0    | 0.0   |       | 0     | 0     |

Table 27: Comparison of HV-surveys, number of events per year, SARFI-values.

The effect of time-aggregation on the 50 percentile and 95 percentile tables for HV Survey D-6 and D-7 are summarized in Table 28 and Table 29 respectively.

| Retained voltage range | 95-percentile values |        |        | 50-percentile values |        |        |
|------------------------|----------------------|--------|--------|----------------------|--------|--------|
|                        | none                 | 10-sec | 10-min | none                 | 10-sec | 10-min |
| 85-90%                 | 26.8                 | 19.0   | 17.6   | 9.0                  | 8.2    | 7.4    |
| 70-85%                 | 27.9                 | 25.5   | 23.5   | 8.8                  | 8.8    | 8.0    |
| 40-70%                 | 18.9                 | 18.3   | 16.7   | 3.2                  | 3.2    | 3.0    |
| 10-40%                 | 6.2                  | 6.2    | 5.7    | 1.2                  | 1.0    | 0.9    |
| 0-10%                  | 6.5                  | 6.6    | 6.2    |                      |        |        |

Table 28: Effect of time aggregation on the indices for HV survey D-6, number of events per year.

| Retained voltage range | 95-percentile values |        |        | 50-percentile values |        |        |
|------------------------|----------------------|--------|--------|----------------------|--------|--------|
|                        | none                 | 10-sec | 10-min | none                 | 10-sec | 10-min |
| 85-90%                 | 9.3                  | 8.3    | 7.0    | 4.2                  | 3.4    | 3.1    |
| 70-85%                 | 15.3                 | 13.1   | 8.2    | 5.3                  | 4.5    | 4.3    |
| 40-70%                 | 6.4                  | 5.0    | 13.2   | 2.2                  | 1.9    | 2.1    |
| 10-40%                 | 1.6                  | 1.6    | 1.6    | 0.4                  | 0.4    | 0.4    |
| 0-10%                  | 2.7                  | 2.3    | 2.0    |                      |        |        |

Table 29: Effect of time aggregation on the indices for HV survey D-7, number of events per year.

#### 3.4.1.4 Comparison of EHV Survey Data

The results for four EHV surveys are summarized in Table 30 and Table 31. The former gives the dip frequency for the 50% site (with the exception of the second value, for survey D-13, which gives the mean value over all sites), the latter the SARFI values.

| Retained voltage | 20-100ms         | 0.1-0.5s      | 0.5-1s      | 1-3s          |
|------------------|------------------|---------------|-------------|---------------|
| 85-90%           | 34.7-25-1.5-3-10 | 2.0-4-1-1-1   | 0.7-1-0-0-1 |               |
| 70-85%           | 41.7-30-3-4-32   | 8.0-3-0.5-8-3 | 0-0-0-1-0   |               |
| 40-70%           | 10.0-13-1-3-13   | 1.3-4-0-2-0   |             |               |
| 10-40%           | 1.7-1-0-0-1      | 0-0-0-1-0     |             | 0.3-1-0.5-0-0 |
| <10%             | 0-0-0-1-0        |               |             |               |

Table 30: Comparison of EHV Surveys, number of events per year, 50%-sites.

| SARFI-Index | D-12   | D-13    | D-13    | D-14  | D-15  |
|-------------|--------|---------|---------|-------|-------|
|             |        | 1996-97 | 1997-98 |       |       |
|             | (mean) | (mean)  | (mean)  | (50%) | (50%) |
| SARFI_90    | 15.4   | 109.7   | 85      | 24    | 61    |
| SARFI_85    | 5.6    | 65.0    | 52      | 19    | 50    |
| SARFI_70    | 2.3    | 13.3    | 19      | 7     | 14    |
| SARFI_40    | 0.7    | 2.0     | 2       | 2     | 1     |
| SARFI_10    | 0.5    | 0       | 0       | 1     | 0     |

Table 31: Comparison of EHV Surveys, number of events per year, SARFI-values.

### 3.4.1.5 Average Statistics

System indices were obtained from a number of network operators in different countries. Most operators provided us with 95% and 50% values for the number of dips per year per site. The results are summarized in Table 32, Table 33, and Table 34, for EHV, HV and MV networks, respectively. For each survey the dip-frequencies were obtained for the 95% site or for the 95% bins (the choice of 95% site or 95% bin does affect the results, but other uncertainties will affect much more). These 95% values were next averaged over all surveys for corresponding voltage levels: EHV (220 and 400kV), HV (66 - 154 kV) and MV (10 – 36 kV).

The UNPEDE format is used for the bins: the columns give duration range in seconds; the rows give range of retained voltage in percent of nominal voltage or pre-event voltage. The duration ranges 20-60 and 60-180 seconds are not shown as no dips in these ranges were recorded.

| Retained voltage | 0.02-0.1 | 0.1-0.5s | 0.5-1s | 1-3s | 3-20s |
|------------------|----------|----------|--------|------|-------|
| 85-90%           | 17.3     | 7.4      | 0.3    | 0.3  | 0     |
| 70-85%           | 26.7     | 6.4      | 0.7    | 0    | 0     |
| 40-70%           | 9.5      | 2.7      | 0.2    | 0    | 0     |
| 10-40%           | 2.3      | 0.2      | 0      | 0.2  | 0     |
| 0-10%            | 1.0      | 0.8      | 0.7    | 0.3  | 0     |

Table 32: measurement results for EHV networks, number of events per year.

| Retained voltage | 0.02-0.1 s | 0.1-0.5 s | 0.5-1 s | 1-3 s | 3-20 s |
|------------------|------------|-----------|---------|-------|--------|
| 85-90%           | 53.0       | 36.0      | 16.4    | 7.0   | 0      |
| 70-85%           | 55.0       | 25.8      | 7.6     | 5.0   | 0      |
| 40-70%           | 30.2       | 15.6      | 4.4     | 1.6   | 0      |
| 10-40%           | 19.4       | 4.8       | 1.0     | 0.6   | 0      |
| 0-10%            | 1.8        | 1.4       | 0       | 1.2   | 0.2    |

Table 33: measurement results for HV networks, number of events per year.

| Retained voltage | 0.02-0.1 s | 0.1-0.5 s | 0.5-1ss | 1-3 s | 3-20 s |
|------------------|------------|-----------|---------|-------|--------|
| 85-90%           | 57.7       | 16.3      | 4.7     | 2.2   | 1.0    |
| 70-85%           | 85.5       | 42.8      | 7.7     | 2.4   | 0.3    |
| 40-70%           | 50.4       | 49.3      | 7.4     | 2.1   | 0.3    |
| 10-40%           | 19.7       | 40.3      | 5.0     | 1.9   | 0.3    |
| 0-10%            | 0          | 2.4       | 1.0     | 2.9   | 2.7    |

Table 34: measurement results for MV networks, number of events per year.

The results for EHV, HV and MV are based on 4, 6 and 4 surveys with 312, 559 and 139 monitor years, respectively. Especially for EHV there is a clear lack of measurement data (one survey contributed 100 of the 123 monitor-years), therefore the actual numbers have limited value. Other uncertainties that should be considered when interpreting the results are the variations in dip frequency among sites and between network. It is not possible to directly compare the results between voltage levels. The results for different voltage levels were obtained in different countries and at different locations. Table 35 gives, for a large survey at each voltage level, the difference between the 95% and the 50% values. The dip frequencies given are the total number of dips within the retained voltage range for duration up to 180 seconds. Note that for survey D-1 the average over all sites is used instead of the value for the 50% site, the latter being unavailable.

| Retained<br>voltage | EHV D-14 |     | HV D-7 |     | HV D-10 |     | MV D-1 |      | MV D-3 |     |
|---------------------|----------|-----|--------|-----|---------|-----|--------|------|--------|-----|
|                     | 95%      | 50% | 95%    | 50% | 95%     | 50% | 95%    | mean | 95%    | 50% |
| 85-90%              | 16       | 5   | 9.3    | 4.2 | 241     | 27  | 208    | 65   | 9.7    | 2.6 |
| 70-85%              | 24       | 12  | 15.3   | 5.3 | 192     | 57  | 351    | 99   | 10.0   | 3.2 |
| 40-70%              | 13       | 5   | 6.4    | 2.2 | 88      | 21  | 290    | 73   | 2.4    | 0.5 |
| 10-40%              | 1        | 1   | 1.6    | 0.4 | 19      | 3   | 185    | 38   | 3.3    | 0.6 |
| 0-10%               | 0        | 1   | 2.7    | 0.0 | 11      | 0   | 23     | 5    | 3.6    | 0.3 |

Table 35: variation of dip frequency among sites, number of events per year.

In Table 36, the dip frequencies for the 50% site are compared for five HV surveys. There is a wide range of dip-frequency values, up to a factor of ten in some cells. A discussion on the causes for this would be outside of the scope of this report, but the reader can refer to IEC 61000-2-8 [18] for more information on the causes.

| Retained<br>voltage | D-6 | D-7 | D-9  | D-10 | D-11 |
|---------------------|-----|-----|------|------|------|
| 85-90%              | 9.0 | 4.2 | 12.0 | 27   | 31   |
| 70-85%              | 8.8 | 5.3 | 15.0 | 57   | 56   |
| 40-70%              | 3.2 | 2.2 | 2.3  | 21   | 21   |
| 10-40%              | 1.2 | 0.4 | 0.3  | 3    | 2    |
| 0-10%               | 0.0 | 0.0 | 0.0  | 0    | 0    |

Table 36: variation of dip frequency among HV surveys, number of events per year for 50% site.

### 3.4.2 CONCLUSIONS REGARDING VOLTAGE DIP MEASUREMENT RESULTS

For voltage-dip measurements one or more clear procedures have to be defined to obtain site indices and system indices. The only conclusion that can be drawn from the data collected within the working group is that there is a wide variation in dip frequency between different sites in one network and between different networks.

## 3.5 LONG INTERRUPTIONS

### 3.5.1 COMMENTS ON BENCHMARKING AND COMPARATIVE REPORTING

Measurement data is not available for individual sites: this section discusses statistics for complete transmission or distribution systems.

Where significant international performance statistics are available for Distribution companies (primarily through company annual reports and the work of organizations such as the IEEE [35] in the US, the CEA in Canada [42], and the CEER [45] in Europe), sources of comparative transmission performance statistics are very limited. Where differences in the specific definitions of indices are a major concern in the case comparisons of Distribution companies, Transmission companies often use very different combinations of indices. These are also often applied differently.

Possibly the most consistent transmission system interruption performance study being undertaken from a benchmarking perspective is that of the Canadian Electricity Association (CEA) in Canada. Fourteen utilities are involved in the study, and 5-year performance reports are generated annually.

These are available to members only (the CEA on the other hand makes the results of a similar distribution performance study available public). The only significant transmission performance surveys reported on by Cigre and UNIPEDDE are [46] and [30]. EPRI has undertaken a transmission reliability benchmark study, but this was based on probabilistic techniques (similar to those applied by the various reliability councils in the USA), and did not address actual interruption performance.

International recommendations in 1999 by Cigre WG 39.04 on measurements of quality in transmission systems are that SAIFI, SAIDI, and SAIRI be used as interruption performance indicators. The specific definition of these is interesting in that they apply to delivery and reception points (generators and inter-connectors) [30]. Despite this Cigre WG 39 recommendation, actual practice indicates that different transmission companies in Europe and Australia use or are proposing to use other sets of reporting parameters. These indices are however used extensively in Canada (through the co-ordination of the CEA project).

Significant efforts to develop more appropriate quality and continuity measurement methods for a competitive industry are being driven by both regulators and utilities. This is evidenced by the large number of information sources (published over the last 3 years) that are listed as reference material in this report. Interruption performance reporting is seen as a component of other reporting requirements for future transmission grids. Additional components include availability, and system constraints [47], [29]. In many cases, incentives are in place or are being considered.

A conclusion on inter-utility benchmarking formulated by the IEEE/PES working group on system design is that performance *"cannot be compared between companies by simply comparing indices...many other factors must be taken into consideration"* [48]. A similar conclusion was reached this year in an Australian attempt at international transmission system benchmarking, i.e. the Australian experience is that these problems make *"inter-company and international comparisons difficult if not impossible"* [47].

The benchmarking of transmission performance is complicated by the combination of unique influencing factors in each country (geography, environmental conditions, load density, the location of generation sources, the degree of excess capacity, network topology, system voltage levels). The dominant benchmarking approach for Transmission companies is therefore based on historical performance of the company itself. This is evident in various countries such as the UK's (OFGEM's work related to the BETTA project - which acknowledges the need for "geographic" differentiation in its proposed standards), Australia (ACCC's project to benchmark each of its transmission companies by the end of the year, based on the last 5 years of data for each utility), New Zealand (TransPower's specific differentiation of planned and unplanned system minutes due to the radial nature of its system). The focus of the CEA study is difficult to assess because of the propriety nature of the information.

| Company / Organisation                 | Interruption measures                                   | Target                        | Actual Performance             |              |         |
|--|---|-------------------------------|--------------------------------|--------------|---------|
|  |   |                               | 1999                           | 2000         | 2001    |
| <b>Company 1</b>                       | Circuit availability                                    | 99%                           | 99.6286%                       |              |         |
|  | Circuit services availability                           | 99.999%                       | 99.9992%                       |              |         |
|  | System minutes (Transmission Code)                      | 5                             | 5                              |              |         |
|  | System minutes (Conventional)                           | -                             | -                              |              |         |
|  | Number of supply interruptions                          | 21                            | 27                             |              |         |
| <b>Company 2</b><br>(mandatory)        | Total number of unplanned interruptions                 |                               | 110                            | 62           | 102     |
|  | Total system minutes (all interruptions)                |                               | 9.7                            | 4.9          | 12.4    |
|  | - system minutes (planned)                              |                               | 2.7                            | 2.8          | 0.9     |
|  | - system minutes (unplanned)                            |                               | 7.1                            | 2.1          | 11.6    |
|  | Underlying system minutes (<= 1 system minute)          |                               | 7.3                            | 4.9          | 4       |
|  | - system minutes (planned)                              |                               | 1.7                            | 2.8          | 0.9     |
|  | - system minutes (unplanned)                            |                               | 5.6                            | 2.1          | 3.1     |
|  | Average supply reliability (%)                          |                               | 99.9972                        | 99.9986      | 99.9963 |
|  | Planned interruption restoration performance            |                               | 94.4                           | 100.0        | 89.5    |
| Unplanned interruption response (%)    |   | 100                           | 100                            | 100          |         |
| <b>Company 2</b><br>(additional)       | Availability (AC system)                                | 98.7%                         | 99.2%                          |              |         |
|  | Availability (HVDC system Bipole 1)                     | 95.0%                         | 97.3%                          |              |         |
|  | Availability (HVDC system Pole 1)                       | 92.5%                         | 95.8%                          |              |         |
|  | Availability (HVDC system Pole 2)                       | 97.7%                         | 98.9%                          |              |         |
|  | Average number of interruptions per supply point        |                               | 0.39                           |              |         |
|  | Every supply point - number of events                   | n/a                           | specified per point            |              |         |
| <b>Company 3</b>                       | Average interruption time (AIT)                         | n/a                           | n/a                            |              |         |
| <b>Company 4</b>                       | Number of incidents                                     |                               | 3                              |              |         |
|  | Average incident duration                               |                               | 68min                          |              |         |
|  | Average Unsupplied Energy Per Incident                  |                               | 292 MWh                        |              |         |
|  | Interconnector A availability                           |                               | 96.2%                          |              |         |
|  | Interconnector B availability                           |                               | 99.7%                          |              |         |
|  | Average annual system availability                      |                               | 95.8%                          |              |         |
| <b>Company 5</b>                       | SAIFI-SI (> 1 minute events)                            | n/a                           |                                |              |         |
|  | SAIFI-MI (< 1 minute events)                            | n/a                           |                                |              |         |
|  | SAIDI   | n/a                           |                                |              |         |
|  | SARI  | n/a                           |                                |              |         |
| <b>Company 6</b>                       | SAIFI-SI  | n/a                           | n/a                            |              |         |
|  | SAIFI-MI  | n/a                           | n/a                            |              |         |
|  | SAIDI   | n/a                           | n/a                            |              |         |
|  | SARI  | n/a                           | n/a                            |              |         |
|  | DPU   | n/a                           | n/a                            |              |         |
| <b>Company 7</b>                       | No. of interruptions (planned, unplanned, incl < 1 min) | n/a                           | n/a                            |              |         |
|  | CI (planned, unplanned, incl < 1 min)                   | 0.65 hrs/yr                   | n/a                            |              |         |
|  | SAIFI   | n/a                           | n/a                            |              |         |
|  | MAIFI   | n/a                           | n/a                            |              |         |
|  | System Minutes (previous year peak demand)              | n/a                           | n/a                            |              |         |
| <b>Company 8</b>                       | Number of interruptions over last 3 years               | 3                             |                                |              |         |
|  | Total hours interrupted over last 3 years               | 9 hrs                         |                                |              |         |
| <b>Company 9</b>                       | Load not served (minutes)                               | n/a                           | 7.4                            | 6            |         |
|  | Customer connection point interruptions (frequency)     | n/a                           | 1.25                           | 1.17         |         |
| <b>Company 10</b>                      | SAIDI   | 23.6                          |                                |              |         |
|  | TSAIFI (100kV)  | 2/year                        |                                |              |         |
|  | TSAIFI (44kV)   | 4/year                        |                                |              |         |
| <b>Company 11</b>                      | System minutes  | 50                            |                                |              |         |
|  | Number of interruptions                                 |                               |                                |              |         |
| <b>Company 12</b>                      | System minutes  |                               |                                |              |         |
|  | Number of interruptions                                 |                               |                                |              |         |
|  | SAIDI   |                               |                                |              |         |
|  | CAIDI   |                               |                                |              |         |
| <b>Regulator 1</b><br>(proposal 2002)  | Circuit availability                                    | to be based on 5 yrs data     |                                |              |         |
|  | Minutes off supply                                      | to be based on 5 yrs data     |                                |              |         |
|  | Average restoration time                                | to be based on 5 yrs data     |                                |              |         |
|  | Hours constrained (intra-region)                        | to be based on 5 yrs data     |                                |              |         |
|  | Hours constrained (inter-region)                        | to be based on 5 yrs data     |                                |              |         |
| <b>Regulator 2</b>                     | Number of incidents                                     |                               | 3 - 10                         |              |         |
|  | Average Unsupplied Energy Per Incident                  |                               | 2 - 292 MWh                    |              |         |
|  | Unavailability (monthly basis)                          |                               | 0.5% - 7.5%                    |              |         |
| <b>Regulator 3</b>                     | Interruption cost mechanism                             | utility to decide on spending |                                | new for 2002 |         |
|  | Number of interruptions                                 |                               |                                |              |         |
|  | Energy not supplied                                     |                               |                                |              |         |
| <b>CEA Survey</b><br>(14 participants) | SAIFI (all interruption - including < 1 min)            | n/a                           | available to participants only |              |         |
|  | SAIDI (all interruption - including < 1 min)            | n/a                           | available to participants only |              |         |
|  | System Minutes (previous year peak demand used)*        | n/a                           | available to participants only |              |         |
|  | SARI  | n/a                           | available to participants only |              |         |
| <b>Cigre 1999</b>                      | SAIFI   | n/a                           | n/a                            |              |         |
|  | SAIDI   | n/a                           | n/a                            |              |         |
|  | SARI  | n/a                           | n/a                            |              |         |

Table 37: Comparison indices / objectives for long interruptions.

## 4 RECOMMENDED QUALITY INDICES

Quality indices provide a few representative numbers that are extracted from a large volume of power quality measurement data. As much as is feasible, the number of quality indices and parameters should be kept at their minimum without losing essential information. They should also be easy to assess, be representative of the actual impact of the disturbances they characterize, and they should last a «lifetime» in order to allow comparison of performance with time.

Furthermore, a common set of power quality indices will allow different system operators, to measure and report quality in a consistent and harmonised manner, either to their clients or to the regulator.

For steady state disturbances, such as harmonics, flicker and unbalance, two categories of indices can be distinguished given their use:

- **Indices for planning purposes.** These are used primarily by the system operator to assess internal quality objectives (planning levels) in setting emission limits for large disturbing loads and evaluating the impact of all disturbing loads on the supply system. These could be detailed indices and be comparable to those used for contractual emission purposes (more than one index may be needed here for controlling the impact of higher emissions allowed for short periods of time) ;
- **Indices for voltage characteristics**, for characterising and reporting system performance. These are used to assess external quality objectives or limits within which any customer can expect the voltage characteristics to remain under normal operating conditions. These should be simple indices and could be used for reporting performance to management, contracting to power quality performance in general and for reporting performance at a regulatory level.

It is important to realise that planning levels should not exceed voltage characteristics. Voltage characteristics represent the total disturbance level that should not be exceeded at any supply points, while planning levels are generally based on a high probability of not being exceeded considering time and space distributions such as EMC. A margin is thus required between those two sets of objectives.

Two levels of indices can be distinguished given their use in reporting system performance:

- **Site indices:** the performance at a specific site;
- **System indices:** the performance of a system.

It is also recognised that more complex indices may be needed by the system operator for investigations, diagnostics or specific contractual application purposes. These specific types of indices were not considered as part of the scope of this working group.

In the following, indices are recommended with the aim of their practical use, to check in a simple way the measurement results with the recommended quality objectives given in chapter 5.

### 4.1 HARMONICS

#### 4.1.1 RECOMMENDED INDICES FOR PLANNING LEVELS

Based on the indices proposed in [1], the working group recommends to compare the actual harmonic levels arising from all distorting loads with the planning levels, by using one or more of the following indices (more than one index or more than one probability value — for example: 99% and 95% may be needed for planning levels in order to assess the impact of higher emission levels allowed for short periods of time such as during bursts or start-up conditions). The basic standard to be used is the IEC 61000-4-30. The minimum assessment period should be one week.

- The **95% probability daily value of  $U_{h,vs}$**  (rms value of individual harmonic components over 'very short' 3 s periods);
- The **99% probability weekly value of  $U_{h,sh}$**  (rms value of individual harmonics components over 'short' 10 min periods);
- The **99% probability weekly value of  $U_{h,vs}$** .

The planning levels for the first two indices may be the same. The planning level for the 99% probability value of  $U_{h,vs}$  may exceed this by a factor (e.g.: 1,25 – 2 times) to be specified by the system operator, depending on the harmonic order and the system and load characteristics (see also [11] for very-short term effect of harmonics). It is worth noting that maximum values can be inflated by transients having rich harmonic contents that should not be considered unless such values are removed from measured values (the flagging concept however as introduced in the IEC 61000-4-30 [4] can only flag data containing transients if they cause the rms voltage to go outside the normal range; therefore using maximum values for harmonic indices may not be relevant).

#### 4.1.2 RECOMMENDED INDICES FOR VOLTAGE CHARACTERISTICS

##### 4.1.2.1 Site index

For practical reasons such as allowing easy comparison of voltage characteristics between LV-MV and HV-EHV, and also for having common monitoring methods, the working group recommends the same site indices for HV-EHV systems voltage characteristics as defined in EN 50160 for LV-MV systems, that is:

- The **95% percentile of weekly value of  $U_{h,sh}$**  (individual harmonic voltages and THD).

##### 4.1.2.2 System index

The recommended system index is the value of the site index not exceeded for a high-percentage of sites. Examples of high-percentile sites are 90, 95 and 99%. The system index should be calculated for each harmonic order separately. Thus the reported values of the system index may, for different harmonic orders, occur at different sites (e.g. The 95% site may not be the same site for the 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, etc ..).

The choice of the percentage of sites for the system index a matter of agreement between the system operator and the regulator.

An alternative approach is to define as a system index the percentage of sites that exceeds the objective in the reporting period.

Depending on the percentage of sites that is allowed to exceed the system index — 1%, 5% or other objective — then at least 100 sites would need to be monitored for the uncertainty to be 1% or less, or at least 20 sites for the uncertainty to be 5% or less, and so on.

System indices should be based on a wide and representative selection of monitoring sites. Full coverage can only truly be obtained if 100% of all sites are being monitored. However by recognising the primary influencing factors and then considering site categorisation it should be possible to install monitors in a targeted way such that it is possible to cover all categories of sites.

Weighting factors can be introduced to take into account the sites not monitored and the difference in importance between different sites. Weighting factors can be based on the number of substations, the number of customers, or the rated power represented by each site. The characteristics and environ-

ments of the circuits and networks being monitored should be considered. The methods for calculating the percentage of sites values and the weighting factors should be indicated.

#### 4.1.3 CONSIDERATIONS ON MONITORING HARMONICS

The accurate measurement of harmonic distortion requires a wide bandwidth instrument transformer. Especially in HV and EHV systems this is hard to achieve with the existing transformers. Capacitive voltage transformers show resonance frequencies as low as 600 Hz (12<sup>th</sup> harmonic in a 50 Hz system). This may seriously affect the results. For this reason, only harmonic measurements using magnetic voltage transformers were reported in chapter 3.

## 4.2 FLICKER

### 4.2.1 RECOMMENDED INDICES FOR PLANNING LEVELS

Recommendations of the working group are that  $P_{st}$  values should be sufficient for assessing planning levels in order to control short term emissions. One or both of the following indices may be used:

- The **95% probability weekly value of  $P_{st}$**  ;
- The **99% probability weekly value of  $P_{st}$** .

The 95% probability value should not exceed its planning level (taking into account the flicker transfer coefficient). The planning level for the 99% probability value may exceed this by a factor (for example: 1-1,5) to be specified by the system operator, depending on the system and load characteristics. (Note that 99% of the week represents about 10 values that may exceed the planning level. The probability that these values occur during the time when customers are sensitive to flicker is low.) The basic standard to be used is the IEC 61000-4-30. The minimum measurement period should be one week.

Another index  $P_{it\ 99}$  weekly was proposed in [2] but is not recommended here.  $P_{it\ 99}$  may actually be equal to the maximum weekly value. Maximum or 99%  $P_{it}$  values may not be relevant because they can be inflated by dips unless such events are flagged according to recent IEC 61000-4-30 and removed from statistical results.

### 4.2.2 RECOMMENDED INDICES FOR VOLTAGE CHARACTERISTICS

#### 4.2.2.1 Site index

As for harmonics, the working group recommends the same site indices for HV-EHV systems voltage characteristics as defined in EN 50160 for LV-MV systems:

- The **95% probability weekly value of  $P_{it}$** .

#### 4.2.2.2 System index

For system indices for flicker, a current limitation is that, in many systems, flicker measurements are often only conducted at few problem sites located nearby large fluctuating loads. Flicker problems tend to be specific and are not likely to be widespread throughout the system. Continuous monitoring of flicker levels at all points of connection with the basic grid should not be necessary, and large expenditures to track flicker levels everywhere in the system may not be justified.

Since only few sites are monitored for flicker, those which are monitored are unlikely to be an unbiased sample from the total population. This situation is not likely to change in many cases and it constitutes a limitation to recommending flicker system indices. Considering the above, WG came to the conclusion that for flicker, a system index should not be recommended for general application.

However in case of systems where permanent flicker monitoring is planned at a large number of sites, it is necessary that a minimum number of the sites be monitored in order to be able to calculate a relevant system index (see 4.1.2.2).

#### 4.2.3 CONSIDERATIONS ON MONITORING FLICKER

- The duration of the measurement period is important. Specific considerations that will impact the assessment include:
  - Network changes that result in significant changes in fault level at the measurement point (PCC of the disturbing customer);
  - Arc furnace charge composition (experience has shown that scrap furnaces using a 100% scrap charge can emit up to 25% higher flicker levels than a furnace charged with 50% scrap and 50% directly reduced iron);
  - Arc furnace charge size (experience has shown that the size of scrap can have a significant effect on emission levels);
  - The effect of thunderstorms on voltage dips and hence severe voltage fluctuations;
  - Long-term effects such as the temporary closure of some industries fed from a busbar;
  - The possible mal-operation or failure of flicker compensators such as SVC's;
  - The effects of possible lower global flicker emission over a week-end, as well as the reduced motor loading on MV and LV networks (subsequently resulting in lower attenuation from HV to LV);
  - Variations in load flicker emission levels according to the process requirements. For example, flicker levels at one substation increased from  $P_{st99} = 0,8$  to just under 1,5 for two 1-week measurements taken 17 months apart. Therefore it is recommended to perform several 1-week flicker measurements in different period of the year.

### 4.3 UNBALANCE

#### 4.3.1 RECOMMENDED INDICES FOR PLANNING LEVELS

Because of the similarity of effects caused by harmonics and voltage unbalance (thermal effects) the working group recommends using similar site and system indices for both.

Thus, the working group recommends to compare the actual level of voltage unbalance arising from all unbalanced loads with the planning level, by using one or both of the following indices (more than one index or more than one probability value – for example: 99% and 95% may be needed for planning levels in order to assess the impact of higher emission levels allowed for short periods of time such as during arc furnace initial phase of scrap melting or start-up conditions of traction loads). The basic standard to be used is the IEC 61000-4-30. The minimum assessment period should be one week. The indices are:

- The **95% probability daily value of  $U_{neg,vs}$**  (rms value of voltage unbalance factor over 'very short' 3-s periods);
- The **99% probability weekly value of  $U_{neg,sh}$**  (rms value of voltage unbalance factor over 'short' 10-min periods);
- The **99% probability weekly value of  $U_{neg,vs}$** .

The planning levels for the first two indices may be the same. The planning level for the 99% probability weekly value of  $U_{\text{neg,sh}}$ , may exceed this by a factor (for example: 1,25 - 2 times) to be specified by the system operator, depending on the characteristics of the system and the loads with their protection devices. It is worth noting that maximum or high probability values can be inflated by transient phenomena and dips or swells that need to be flagged and removed from measured values.

#### 4.3.2 RECOMMENDED INDICES FOR VOLTAGE CHARACTERISTICS

##### 4.3.2.1 Site index

The working group recommends the same site indices for HV-EHV systems voltage characteristics as defined in EN 50160 for LV-MV systems, that is:

- The **95% percentile of weekly value of  $U_{\text{neg,sh}}$**  (Voltage unbalance factor – negative sequence component – over 10 min periods).

##### 4.3.2.2 System index

The recommended system index is the value of the site index not exceeded for a high-percentage of sites. Examples of high-percentile sites are 90, 95 and 99%.

The choice of the percentage of sites for the system index is a matter of agreement between the system operator and the regulator.

An alternative approach is to define as a system index the percentage of sites that exceeds the objective in the reporting period.

For further details on how to assess the system index, refer to 4.1.2.2.

#### 4.3.3 CONSIDERATIONS ON MONITORING VOLTAGE UNBALANCE

It is also important to stress that due to measurement inaccuracies of potential transformers or due to unbalanced secondary load-burden, and inaccuracies in other parts of the measurement chain, the overall accuracy of the measurement system may be limited especially in the case of voltage unbalance because of the large impact on results even from small errors.

### 4.4 VOLTAGE DIPS

#### 4.4.1 SINGLE-EVENT INDICES

Single-events indices are used for troubleshooting and diagnostics. The calculation of single-event indices is an intermediate step in the calculation of site indices.

The recommended single-event indices are the retained voltage and duration of each voltage-dip event which shall be calculated in accordance with IEC 61000-4-30. It is recommended to measure the voltage in all three phases.

The value of the dip-starting threshold used to start the recording of the dip may affect the number of shallow dips captured. When dip recordings are used to calculate site indices, the dip-starting threshold should be outside of the cell boundaries used to present the site indices in a voltage-dip duration table. The choice of the dip-ending threshold affects the duration value. The value used should be in-

licated when the duration values are used to calculate site indices. No specific threshold value is recommended: it is for the user to decide when a temporary reduction of the voltage is counted as a voltage dip.

It is for the user to decide whether the dip-starting threshold is referenced to the nominal or declared voltage or to the sliding voltage reference, but this should be stated.

#### 4.4.2 SITE INDICES

The calculation of site indices is an intermediate step in the calculation of system indices. Site indices are used for compatibility assessment between sensitive equipment and the power supply and can be used as an aid in the choice of a voltage-dip mitigation method. They can also be used to provide information to local customers on the voltage quality e.g. for the follow-up of premium power contracts.

Site indices are calculated from single-event indices, i.e. the retained voltage and the duration obtained for all voltage-dip events at one site during a certain period of time. At locations where seasonal variations in the number of dips can be expected, the monitor period should be an integer multiple of one year. For locations with a strong seasonal variation in the event frequency, a three to five-year monitoring period is recommended to incorporate year-to-year variations in the seasonal effects.

Site indices can be presented in a number of different ways, among which are:

- as a voltage-dip table in accordance with the UNIPEDA-disdip recommendation or the recommendations in IEC 61000-2-8;
- as a contour chart according to IEEE 1346;
- as the number of events more severe than a certain curve (i.e. the ITIC or the SEMI F47 curve) or below a certain retained voltage (SARFI indices as in IEEE Std 1564 draft 5);
- in any other way most suitable for the specific site and application.

The recommended site-indices are the remaining voltage in percent and the duration in milliseconds. It should be indicated if the pre-event or nominal voltage is used as a reference to calculate the relative remaining voltage. When using pre-event voltage, the sliding reference, as defined in IEC 61000-4-30, should be used. The sliding-reference window may be used in HV and EHV systems with a relatively large variation in normal-operation voltage, when HV/MV transformers are equipped with on-line tap changers.

Depending on the application a high or low level of detail may be chosen. For compatibility assessment between equipment and supply, a high level of detail is recommended. When site indices are calculated as an intermediate step in the calculation of system indices, the way of presentation of the site indices should allow for the calculation of the system indices.

In many cases time aggregation is used to prevent double counting of events close together in time. Different methods of aggregation are in use, each with their advantages and disadvantages. One possible method is the following: the retained voltage of the aggregated event is the lowest of the values of the individual dips; the duration of the aggregated event is the longest of the durations of the individual dips. When events are very close together in time (e.g. less than one second) the duration of the aggregated event is the sum of the durations of the individual dips (see also 4.4.4).

The monitor availability needs to be considered in calculating the event frequencies for the site indices. When a monitor is unavailable during a period of (possible) heavy voltage-dip activity, it may be decided to flag the data obtained for that site for the remainder of that year.

#### 4.4.3 SYSTEM INDICES

System indices are used by the network operator to assess the performance of a whole system. They can be used to compare year-to-year performance, where the effect of weather variations should also be considered. The results of such a performance assessment or comparison can be used as a basis for improvements in the system. The indices are not a benchmark by which to judge different networks against each other but can be used to identify typical levels of disturbances for various types of network and for ongoing monitoring of any one network. Geographic or climatic differences from one region to another, or disparities in the load density, easily explain why the characteristics of the supply cannot be the same everywhere, for instance, in urban areas versus rural areas, or on systems with underground cables versus overhead lines.

System indices are calculated from the site indices of all monitored sites over a certain region. A region may consist of the network operated by one company, one voltage level, one country or province, etc.

System indices for voltage dips can be presented in the same way as site indices. The required level of detail is typically lower for system indices than for site indices. The choice of bins should represent typical fault-clearing times, other system properties, and typical equipment susceptibility, depending on the application. Different bins may be considered for overhead and underground networks, and for distribution and transmission networks. The actual choice of the bins is an internal affair for the network operator and as such outside of the scope of this document.

System indices can be calculated either from the average of the site indices or from the value not exceeded by a high-percentage of sites being monitored (ex. 95%). Weighting factors can be introduced to take into account the sites not monitored and the difference in importance between different sites. Weighting factors can be based on the number of substations, the number of customers, or the rated power represented by each site. The construction and environments of the circuits and networks being monitored should be considered. The methods for calculating the high-percentile site values and the weighting factors should be indicated.

It is recommended for system indices derived from monitoring at HV or EHV, that voltage dip measurements use the phase-to-phase voltages because they give statistically an image that is closer to what the end-users equipment see than phase-to-neutral measurements. If phase-to-neutral measurements are carried out, a method [51] gives the possibility to estimate the phase-to-phase rms voltages from phase-to-neutral measurements.

Full coverage can only truly be obtained if 100% of all sites are being monitored. However by recognizing the primary influencing factors and then considering site categorization it should be possible to install monitors in a targeted way such that it is possible to cover all categories of sites. The results for each category can then be mapped on to non-monitored sites, with a verification based on known fault statistics.

#### 4.4.4 TIME AGGREGATION

Several publications mention time aggregation as a possible method of preventing double-counting of events. The reasoning is that two identical voltage dips which occur within a short time window will often not have double the impact of each individual event. Equipment will in most cases either trip on the first event or not trip at all. The discussion on the choice of time-aggregation window remains open. To this effect, it may be worth noting that a recent study for EPRI [24] found that the cost of two

one-second interruptions separated a few second in time cause economic damage which is about twice the damage due to a single one-second interruption.

When collecting voltage-dip data it often shows that voltage dips have the tendency to occur in clusters. The time between events is not randomly distributed but instead shorter times between events are more common than would be expected.

There are several reasons for merging events that are close in time into one event.

- When two identical voltage dip events occur with a few minutes separation, the effect on end-use equipment will be the same as that of one single event. If the first event will cause the equipment to trip the production process will still be down when the second event occurs. If however the equipment manages to ride through the first event it will equally ride through the second event. Thus two events that are separated in time less than the “production recovery time” may be aggregated into one single event. In case the two events are different, the most severe one will determine the behaviour of the equipment.
- Two voltage dips may be due to essentially the same event in the power system. The standard example is unsuccessful reclosing after a fault. Any customers not on the faulted feeder will experience two voltage dips with the same retained voltage. The duration may be different because of difference in breaker characteristic. Another example is a recurrent fault. Such a power-system event may lead to a number of voltage dips separated seconds through minutes in time.
- The algorithm used for characterising voltage dips may detect the end of a dip before the event is actually over. The voltage may recover above the dip-ending threshold for a few cycles and then drop below the threshold again.

For events very close in time (i.e. the new event comes within a certain aggregation window after the end of the previous event) it is appropriate to define an aggregated event with a duration equal to the sum of the durations of the individual events. The retained voltage of the aggregated event is equal to the lowest of the values for the individual events. Reasonable values for the aggregation window are between a few cycles and a few seconds.

As a second stage of aggregation, events within a larger window, the following time-aggregation algorithm is appropriate: the duration of the aggregated event is equal to the largest value for the individual events; the retained voltage of the aggregated event is equal to the lowest value for the individual events. Reasonable values for the time aggregation of the second stage of aggregation range between 10 seconds and half an hour.

The discussion is ongoing on where it is appropriate to use time aggregation and, if it is to be used, which aggregation time to use. At this stage it is not possible to make recommendations on this.

With some surveys aggregation is not based on the time elapsed since the end of the previous voltage dip but instead on the time elapsed since the start of the previous voltage dips. This will lead to somewhat higher apparent event frequencies in some cases. An example of a sequence of voltage dips that can be aggregated in two different ways is shown in Figure 14, where a time-aggregation window of 100 seconds has been assumed. Using the time since the end of the previous dip these five dips will be aggregated as one event. Using instead the time since the start of the previous will result in two aggregated events, the first one consisting of three voltage dips, the second of two dips.

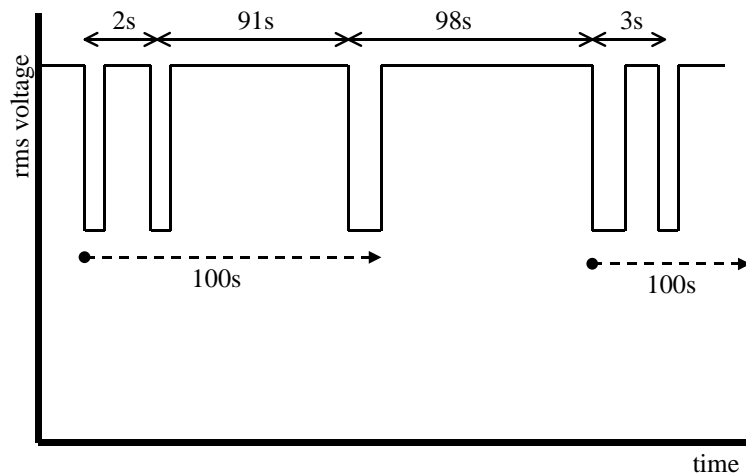


Figure 14: Sequence of voltage dips that can be aggregated in two different ways.

The choice of aggregation time for HV and EHV measurements can be made easier when information is available on the autoreclosure time used at the voltage level where the monitor is located and higher voltage levels. A review of reclosing times and practices for some countries (see **Table 38**) shows that autoreclosure time, and thus the window in which one may expect a second event, vary significantly even within one country. It goes from a fraction of a second to few tens of seconds, but it is generally less than 1 minute in the case of multiple reclosing attempts.

| Country | Voltage level | Reclosing time |                  |
|---------|---------------|----------------|------------------|
|         |               | first attempt  | further attempts |
| Belgium | EHV           | 1 - 10 s       | -                |
|         | HV            | 0.3 - 10 s     | -                |
| Canada  | MV            | 2 - 10 s       | 10 - 20 s        |
|         | HV            | 0.5 - 1.5 s    | -                |
| Finland | EHV           | 0.75 - 5 s     | -                |
|         | HV - EHV      | 0.4 s          | 30 - 60 s        |
| Germany | EHV           | 0.4 - 1.2 s    | -                |
| Japan   | EHV           | 0.4 - 1 s      | 3 - 60 s         |
|         | HV            | 0.4 - 60 s     | -                |
| USA     | EHV           | 0.25 - 5 s     | 10 - 15 s        |
|         | MV            | 0.5 - 3 s      | 10 - 15 s        |

Table 38: Example reclosing times in some countries or jurisdictions.

#### 4.4.5 FUTURE DIRECTIONS

New methods are being proposed in the literature to determine direction (upstream, downstream) and cause (fault, motor, transformer, other) of a voltage-dip event. In addition, there are new indices based on phase-angle jump, symmetrical component voltages, point-on-wave, etc. Methods need to be developed to present site indices when additional single-event indices like phase-angle jump and symmetrical component voltages are included. Site indices for three-phase characterization of dips may consist of one set of indices or of different sets of indices for different types of dips. Implementation of these new methods and indices could provide systematic indications on the causes of dips and allow better prediction of the effects of voltage dips on different type of sensitive equipment. The effect on the site indices of the propagation of voltage dips to lower voltages should be investigated.

Stochastic prediction methods are needed to obtain voltage dip site indices and system indices, thus avoiding long and expensive monitoring programs. Recommendations to that effect are given in IEEE Std.493. Methods for voltage-dip state estimation need to be developed, where the site indices for non-monitored sites are estimated from the site indices for monitored sites.

There are a number of monitoring projects going on around the world and we need to learn from their experiences and recommendations. In order to achieve this, measurements need to be done based on a common standard (e.g. IEC 61000-4-30) in order to enable comparison of results.

## 4.5 LONG INTERRUPTIONS

### 4.5.1 MV INDICES: DISTRIBUTION SYSTEMS

The system interruption indices defined in IEEE 1366 for MV systems are recommended, i.e. SAIFI, MAIFI, SAIDI, CAIDI. These are based on the number of customers interrupted.

*SAIFI (System Average Interruption Frequency Index):* The average number of sustained interruptions per customer during the year. It is calculated by dividing the total annual number of customer interruptions by the total number of customers served during the year, i.e.:

$$SAIFI = \frac{\sum N_i}{N_T}$$

Where:

- $N_i$  is the number of interrupted customers for each (sustained) interruption event during reporting period;
- $\sum N_i$  is the total number of (sustained) interruptions to customers during reporting period;
- $N_T$  is the total number of customers served
- $i$  an interruption event (sustained interruption in this case).

*MAIFI (Momentary Average Interruption Frequency Index)* is the average number of momentary interruptions. It is calculated as the total number of momentary customer interruptions, divided by the total number of distribution customers averaged over a year and is expressed as follows:

$$MAIFI = \frac{\sum NM_i}{N_T}$$

Where:

- $\sum NM_i$  is the total number of momentary interruptions to customers during reporting period;

*SAIDI (System Average Interruption Duration Index):* The average duration of sustained interruptions for customers who experience interruptions during the year – i.e. the average time during which customers' power supply is interrupted during a year. It is determined by dividing the sum of all durations of sustained interruptions to customers by the total number of customers and can be expressed as follows:

$$SAIDI = \frac{\sum r_i N_i}{N_T}$$

- Where:  $r_i$  is the duration of each sustained interruption.

SAIDI is commonly referred to in Europe as *Customer Minutes Lost (CML)*, and is often also expressed in terms of minutes per 100 customers.

*CAIDI (Customer Average Interruption Duration Index)*: The average time required to restore service to the average customer per sustained interruption. It is determined as the sum of all customer interruption durations, divided by the total number of customers' interruptions.

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{\sum r_i N_i}{\sum N_i}$$

#### 4.5.2 HV AND EHV INDICES: TRANSMISSION AND SUB-TRANSMISSION SYSTEMS

Three categories of interruption indices are presented in order to take into consideration different interruption reporting requirements that may emerge from utility management, regulators, or customers. These three categories are based on different philosophies, and describe different aspects of interruption performance, i.e.:

- Connection Point Interruption Performance (CPI);
- End-Customer Load Interruption Performance (CLI);
- System Interrupted Energy Performance.

The three philosophies are discussed in detail below. Table 40 summarizes the differences between the indices recommended in accordance with each of these philosophies. Allowance has been made for different methods of calculating the various indices. Table 41 provides a template for guiding users in applying the indices and declaring how these are calculated.

When reporting these indices, it is recommended that forced interruptions and planned interruptions be reported separately. The indices below address primarily forced interruptions.

Some indices (System Minutes and System Energy Availability or Unavailability) may be used with any of the above philosophies. These are treated separately below.

#### Recommended application for reporting purposes

It is generally recommended that companies select one of the three philosophies for system reporting purposes and use the set of indices defined for the selected philosophy. Some companies may wish to provide a full description of the system interruption performance using more than one philosophy. Indices that are equivalent have been indicated to avoid duplication in the reporting process (see Table 40).

Changes to the specific definitions of the indices are not recommended (e.g. use of the *connection point interruption* index SAIDI-CPI whilst using the calculation of duration based on the definition used to derive the *end-customer* index SAIDI-CLI). Should any such underlying definition changes be made, these should be declared together with the reporting template in Table 41.

It is recommended that interruption performance be differentiated between “momentary” (short) and “sustained” (long) interruptions, based on a declared interruption duration. The choice of the duration used to differentiate these interruptions may be based on one of two philosophies:

- A requirement to differentiate between automatic and manual operator interventions due to transmission-caused interruptions. The recommended value in this case is *1 minute*, although specific companies may declare any other value. As a guideline, this philosophy is recommended where *connection point interruption* performance reporting is undertaken;
- A requirement to align transmission interruption reporting with distribution reporting used in a given country. Typical durations used in distribution reporting are: 1 minute, 2 minutes, 3 minutes (EN 50160), or 5 minutes (IEEE 1366). This philosophy is recommended when *end-customer load interruption* performance reporting is undertaken.

### Terminology:

Terminology used in this section is defined below:

A “*connection point*” (see 4.5.2.1).

A “*circuit outage*” is an outage of a circuit. This may not result in a downstream interruption (e.g. in the case of a parallel network).

An “*interruption*” refers to the general case for any event that may have an impact on any of the above indices. This may or may not be associated with a physical opening of a transmission circuit. Where a specific type of interruption is implied, this will be specifically referred to as a “*connection point interruption*” or an “*end-customer load interruption*”.

A “*connection point interruption*” refers to a disconnection of two systems at an interface point between the transmission company and its direct customer (e.g. a distribution company). This may or may not result in an actual loss of load.

An “*end-customer load interruption*” refers to the case where the load of a single customer is lost either due to a connection point interruption or due to specific measures taken to remove load from the system for the purpose of protecting the system (note that load shedding may or may not be associated with a connection point interruption).

A “*load interruption incident*” refers to an incident that results in load being interrupted. A load interruption incident may be associated with several end-customer load interruptions.

A “*load interruption event*” refers to the time-aggregation over one or more *load interruption incidents* that result in load being interrupted.

An “*end-customer*” refers to an end-user of electricity (for example a distribution company may be a *customer* of a transmission company, and may have many *end-customers* within its network).

“*Estimated Energy Not Served*” (*EENS*) refers to estimated energy (MWh) not served due to an interruption.

#### 4.5.2.1 Connection Point Interruption Performance Philosophy

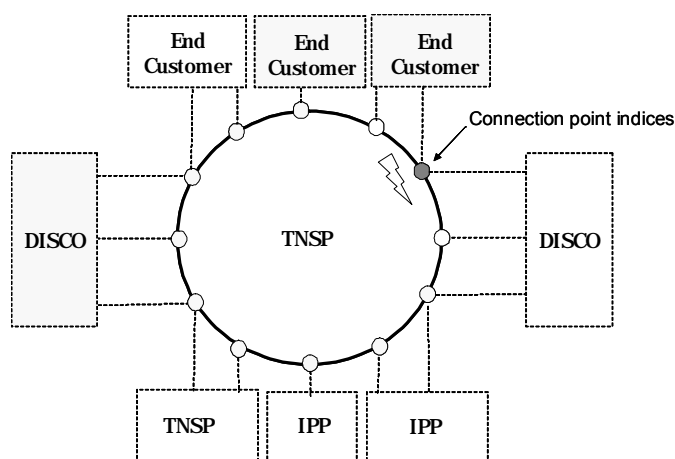
In fully liberalized electricity markets, there is a requirement for the interruption performance of a transmission company to be described and reported separately from the (negative or positive) impact of the networks on its customers, i.e. distribution companies, large directly connected end-customers, interconnections with other transmission grids, and power producers.

For example, the loss of supply to one distribution company supply point may or may not result in an interruption to customers within the distribution company. Whether such an interruption will be seen by customers will depend on the nature and state of the distribution network at the time of the incident. Reporting only events that affect end-customers may therefore not reflect an underlying degradation of the transmission system interruption performance separately from the improvement or degradation of the distribution system performance. In future liberalized markets, it may also be possible that any other supply to the distribution company comes from another distribution or transmission company (i.e. customer load may not be lost, but the backup supply is from another company). Actions taken by a transmission company to increase the reliability of its supply are therefore more accurately reflected.

Connection point interruption indices address this aspect of interruption performance by describing the reliability and availability of all individual interfaces between the transmission system and the networks of its various customers. The indices are largely independent of the reliability and availability of customer networks.

Figure 15 illustrates the connection point philosophy, where interruptions of the supply to the interface points of the transmission network service provider (TNSP) are considered independently of any inter-connections within the distribution company (DISCO), the end customer, or independent power producers (IPP's).

Note that this in fact is similar to distribution indices as interruptions are counted without taking into consideration the effect of possible backup generation equipment.



**Figure 15: Connection point indices defined at the interface between the transmission company and its customers.**

### Recommended Connection Point Indices

The following system indices are recommended specifically for describing the *frequency and duration* associated with connection point interruption performance:

- Average *frequency* of sustained *connection point interruptions* per year: SAIFI-CPI;
- Average *frequency* of momentary *connection point interruptions* per year: MAIFI-CPI;
- Average *total duration* of all sustained *connection point interruptions* per year: SAIDI-CPI (see note below);
- Average *duration* of a sustained *connection point interruption* during the year: SAIRI-CPI (see note below).

*Note: Similar indices for momentary events are not meaningful and by including momentary events with sustained events in SAIDI, SAIRI, these indices will improve for more momentary events.*

These indices have a direct physical meaning – i.e. avoidance of a single connection point interruption will directly affect SAIFI (i.e. improving the reliability of the connection point that may supply various customers). Note that a major event on the transmission system (affecting many supply points) will also affect all of the indices. Comparison of year-on-year “underlying performance” may require the removal of such major events.

Avoiding a connection point interruption may be done, in the example of an overloaded supply circuit due to the outage of another parallel circuit, by shedding specific loads within the network of a customer. Note that the reliability of supply to other loads is not impacted by this. For this reason, an additional index is required to include reporting on the number of such load shed incidents. A similar consideration applies to a situation where demand is reduced by a deliberate reduction in steady-state voltage.

One of the following indices is recommended to be used to define *customer load loss* in conjunction with connection point indices:

- Number of *system minute events of degree severity* 0, 1, 2, or 3: SM(0), SM(1), SM(2), SM(3) (see 4.5.2.4);
- The number of *load interruption events*. (this is the sum of all SM events).

These indices include customer load interruptions associated with a connection point interruption, as well as a load shedding event not associated with a load interruption.

An event refers to a time aggregation of several incidents. For example, where customer load is tripped due to a transformer overload, restored and tripped again, the two incidents may be counted as one event. In the case of system minutes, the total estimated ENS (kWh) is used to determine the degree severity.

The following may be excluded from the SM and load interruption event indices:

- In some cases, customers may have contracted load shedding. The above indices do not take the load loss impact on end-customers into account;
- Events not caused by the transmission company.

### **Definition of a connection point**

A transmission *connection point* is defined as the interface (border) between the transmission network and another transmission network, a distribution company, large end-customer, or producers. It is the point up to which the transmission company has responsibility and control over.

Note: Connection point indices may sometimes be separated into “reception points” indices (associated with power producers) and “delivery point” indices associated with end-users and distribution companies. However, the latter distinction becomes less clear in the case of transmission interconnections, and where more independent power producers are connected in distribution networks. The above more general definition is therefore recommended, as it describes the connection point performance to all transmission customers.

Connection points may be located on the:

- EHV busbar (e.g. in cases where EHV/HV transformers are owned and operated by the Distribution Company);
- HV or MV busbar (e.g. where the busbar is owned and operated by Transmission Company);
- Low voltage side of the EHV/HV step-down transformers, (e.g. where the busbars are owned by Distribution Company);
- Remote line terminals (e.g. where the lines are owned and operated by the transmission company).

*Note In some cases the transmission substation fence defines the limits of responsibility for the transmission and distribution companies. In this case one of the above definitions may still be applied. The counting of a delivery point interruption will be determined by where the fault has occurred (i.e. within the transmission substation it is counted, outside not).*

An individual *connection point* may be defined by one of the following:

- a *complete busbar* (including line breakers / section breakers where these are normally closed),
- *individual sections of a busbar* (typically where the couplers are normally open), or
- *individual breaker terminals*

In the first two cases, an interruption related to any part of the connection point is considered as a connection point interruption.

The definition applied by a transmission company should be:

- Declared when reporting connection point indices;
- Consistent for the whole system (i.e. same definition applied at all points);
- The same for each reporting period.

*Note: Where customers are involved in benchmarking, the same definition should be applied, as the results will differ.*

## **Duration**

The duration of a *connection point interruption* is defined from the moment of loss of supply to the connection point to the time when supply is made available to the customer (e.g. Distribution Company) side of the connection point. If the Transmission system itself limits the load recovery subsequent to the reconnection, the additional duration is counted. Delays in restoring supply to customers within the distribution system do not impact the duration.

### **4.5.2.2 End-Customer Interruption Performance Philosophy**

The frequency and duration indices associated with *connection-point interruption* performance reporting may not correlate with the actual impact on customers due to the underlying interconnected nature of some distribution systems (i.e. the potential of multiple supply points to the customer).

*End-customer interruption performance indices* describe the reliability of the supply for transmission-caused events to actual end customers (i.e. taking into consideration the effect of the underlying distribution system). This requires information from Distribution customers on the number of customers

affected, and the duration (particularly in the case of stepped restoration). Large customers are counted the same as small customers.

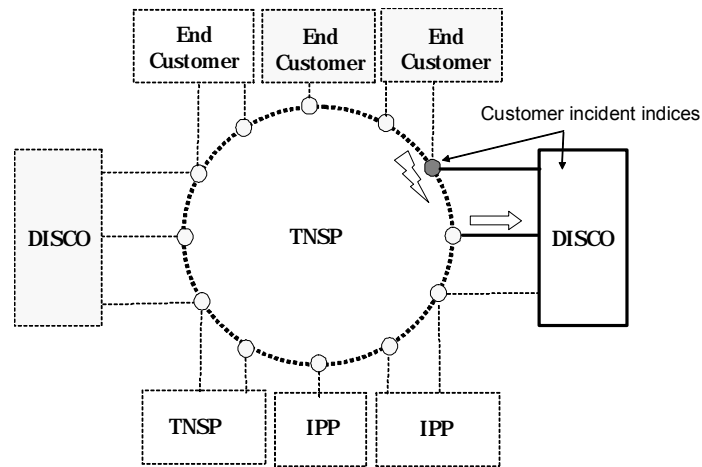


Figure 16 : Customer load interruption events.

Recommended indices for this philosophy are shown in Table 40.

#### Duration

The duration of an *end-customer point interruption* is defined from the moment of the interruption to the connection point to the time when supply is restored, or made available to end-customers (which ever is shorter). In the case of stepped restoration, the duration is calculated individually for each of the restoration steps.

#### 4.5.2.3 System Interruption Energy Philosophy

In order to report on the actual impact on customers using *end-customer interruption* indices, information is required from the distribution company (e.g. the number of customers affected). Methods for approximating such performance reporting using the estimated energy not supplied (EENS in MWh) and the size of the load interrupted (MW) may be applied.

#### Recommended Indices

The following system index definitions are recommended:

System Average Interruption Time (AIT):

$$AIT = \frac{\sum (EENS - SI) \cdot 8760.60}{YEC \cdot 10^6}$$

Where:

$EENS-SI$  = Estimated Energy Not Supplied for each sustained interruption (MWh);

$\Sigma (EENS-SI)$  = sum of all EENS-SI over a 12 month period (MWh);

YEC = Yearly Energy Consumption in the system (TWh).

The calculation of EENS-SI is applied only for sustained interruptions. It may be estimated by (interrupted power x event duration).

$$EENS-SI = T.PNS$$

Note that for distribution systems this measure may be considered an approximation of SAIDI and CML under the assumption that all customers are the same size. This assumption is not as suitable for transmission systems, where the size of a single customer may range from 10 to 1000 MW. It therefore represents a theoretical adaption of SAIDI for the transmission system.

#### System Average Interruption Duration (AID):

It is calculated by:

$$AID = \frac{\sum(T.PNS)}{\sum PNS} = \frac{\sum ENS - SI}{\sum PNS} \quad (\text{min / Interruption})$$

where:

- T = duration of each sustained interruption;
- PNS = interrupted power (it is then a weighted average in function of the interrupted power).

*NOTE: For distribution systems this measure may be considered an approximation of CAIDI under the assumption that all customers are the same size. It represents a theoretical interpretation of interruption time for the system.*

#### System Average Interruption Frequency (AIF)

It is calculated by:

$$AIF = \frac{AIT}{AID} \quad (\text{interruptions / year})$$

*NOTE: For distribution systems this measure may be considered an approximation of SAIFI under the assumption that all customers are the same size. It represents a theoretical interpretation of interruption probability for the system.*

#### **4.5.2.4 General System Indices**

The following indices may be applied in conjunction with any of the reporting philosophies applied. They provide additional information on the system performance.

##### **System Energy Unavailability or Availability:**

$$\text{Unavailability} = 100.EENS / (YEC) \quad (\%)$$

$$\text{Availability} = 100*(1 - \text{Unavailability}) \quad (\%)$$

*EENS* = Estimated Energy Not Supplied for each interruption, including monetary interruptions, sustained interruptions, and load reduction events (MWh). Only events associated with the transmission system interruptions and constraints should be included. Generation-initiated events may be excluded.

#### **System minutes**

A measure of the severity of incidents on the system. The definition is:

System minutes, i.e. energy not supplied as a function of the size of the system.

$$SM = \frac{60 \cdot ENS}{PD}$$

where:

*ENS* = Total Energy Not Supplied from all incidents (MWh);

*PD* = Peak System Demand for reporting year (MW).

The estimated energy not supplied (ENS) includes transmission-caused events where customer loads were interrupted or shed or reduced, that are not associated with a connection point interruption. It includes momentary events. ENS caused by voltage dips may be excluded. The calculation of estimated energy not served may be calculated as MW interrupted \* duration of the event. Where information is available on stepped restoration, this may be calculated as the total for each restoration step.

### Indices based on a severity index for individual incidents

The indices proposed are:

- *SM < 1*: The *cumulative system minute value* as a result of single events within an individual system minute contribution of less than 1 minute. This provides an indication of the annual trend in "normal" interruption severity.
- *SM events of degree severity*: The number of customer interruption events with a given degree of severity. The degree of severity may be 1, 2, or 3, depending on the severity of the event. This provides a description of the severity of the individual events.

| Degree | Description   | SM       |
|--------|---|----------|
| 0      | Unreliability condition normally considered acceptable for some systems | < 1      |
| 1      | Significant impact on one or more customers but not considered serious  | 1 to 9   |
| 2      | Serious impact on customers   | 10 to 99 |
| 3      | Very serious impact on customers  | >= 100   |

**Table 39: System minutes degree of severity definitions.**

Table 40: Categorization of recommended interruption indices for reference when selecting a group of measures to describe performance.

| Categorisation                   | Definition  | Connection Point Philosophy  | End-Customer Philosophy                  | System Energy Philosophy |
|----------------------------------|---|--|--|--------------------------|
| Frequency                        | Average frequency of <i>connection point</i> interruptions per year (no./year)            | SAIFI-CPI (sustained)<br>MAIFI-CPI (momentary)   |  |                          |
|                                  | Average frequency of <i>customer</i> interruptions per year * (no./year)                  |  | SAIFI (sustained)*<br>MAIFI (momentary)* |                          |
|                                  | Average <i>system</i> interruption frequency (no./year)                                   |  |  | AIF                      |
|                                  | Number of interruption events associated with load loss (no./year)                        | No. of SM events with system minutes of degree 0,1,2,3<br><b>OR</b><br>Number of load interruption events                          |  |                          |
|                                  | Number of forced <i>load reduction</i> events – no delivery point interruption (no./year) | Number of forced load reduction events (NLRE)  |  |                          |
| Individual interruption duration | Average duration of a <i>connection point</i> interruption (min)                          | SAIRI-CPI  |  |                          |
|                                  | Average duration of a <i>customer</i> interruption * (min)                                |  | CAIDI*                                   |                          |
|                                  | Average <i>system</i> interruption duration (min)   |  |  | AID                      |
| Total duration of interruptions  | Average total duration of <i>connection point</i> interruptions per year (min/year)       | SAIDI-CPI  |  |                          |
|                                  | Average total duration of <i>customer</i> interruptions per year *(min/year)              |  | SAIDI*                                   |                          |
|                                  | <i>System</i> interruption time - system not able to provide energy (min/year)            |  |  | AIT                      |
| Interruption Severity            | System minutes (system min/year)  | Sum of system minutes for events < 1 system minute<br>Individual event severity for system minute events ≥ 1 reported individually |  |                          |
| Availability / Unavailability    | System energy availability (%) or<br>System energy unavailability (%)                     | Availability <b>OR</b><br>Unavailability   |  |                          |

\* NOTE (DX): Customer load loss philosophy can be applied according to distribution rules for defining customers. This provides some alignment between performance of the distribution company and the transmission company. Use of this philosophy however requires knowledge of the number of customers affected for each event (this can only be provided by the distribution company). Use of a unique definition of the number of customers is not recommended, however where this is used, the unique definition should be clearly described when reporting.

## RECOMMENDED DOCUMENTATION ACCOMPANYING REPORTING OF SYSTEM INTERRUPTION INDICES

To allow the methods applied to interruption performance to be identified for interpretation or comparative purposes, a template for addressing the various considerations should be completed. The options recommended by the working group have been indicated, but other choices may be made, based on local requirements.

The interruption reporting philosophy should be categorized and declared as being either:

- “connection point interruption performance”,
- “end-customer interruption performance”, or
- “system interruption performance”.

**Table 41 : Recommended documentation accompanying reporting of system interruption indices.**

| TEMPLATE  | Connection Point Philosophy        | End-Customer Philosophy            | System Energy Philosophy           |
|---|------------------------------------|------------------------------------|------------------------------------|
| <b>Forced and planned interruptions</b>   |                                    |                                    |                                    |
| (a) Only forced interruptions included in calculation of indices  | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (b) Forced and planned interruptions included   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| <b>Interface voltage level (multiple interface voltages may be selected, indicate definition)</b>                       |                                    |                                    |                                    |
| (a) EHV   | <input type="checkbox"/> ..... %   | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (b) HV  | <input type="checkbox"/> ..... %   | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (c) MV  | <input type="checkbox"/> ..... %   | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (d) Other   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| <b>Definition of a connection point (only one should be selected as this should be consistent for the whole system)</b> |                                    |                                    |                                    |
| (a) Single voltage level at the interface   | <input type="checkbox"/>           |                                    |                                    |
| (b) Busbar / bus section  | <input type="checkbox"/>           |                                    |                                    |
| (c) Individual circuits terminations (e.g. breaker or transformer or line terminals)                                    | <input type="checkbox"/>           |                                    |                                    |
| (d) Other   | <input type="checkbox"/>           |                                    |                                    |
| <b>Customer types used in indices (several types may be selected)</b>   |                                    |                                    |                                    |
| (a) Distribution companies  | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (b) Large end-customers   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (c) Inter-connections (e.g. other transmission companies)   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (d) Power producers   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (e) Other   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| <b>Definition of sustained vs. momentary interruption duration (indicate duration used)</b>                             |                                    |                                    |                                    |
| (a) Philosophy based on automatic vs. manual transmission interventions (recommended 1 min)                             | <input type="checkbox"/> ..... min | <input type="checkbox"/> ..... min | <input type="checkbox"/> ..... min |
| (b) Philosophy based on distribution interruption duration definitions (typically 1 min, 2 min, 3min, 5min)             | <input type="checkbox"/> ..... min | <input type="checkbox"/> ..... min | <input type="checkbox"/> ..... min |
| <b>Definition of an interruption</b>  |                                    |                                    |                                    |
| (a) Only three-phase events counted   | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| (b) Single-phase events also counted  | <input type="checkbox"/>           | <input type="checkbox"/>           | <input type="checkbox"/>           |
| <b>Definition of number of customers affected</b>   |                                    |                                    |                                    |

|  |                                  |                                  |                          |
|--|----------------------------------|----------------------------------|--------------------------|
| (a) Total number of distribution customers (i.e. including distribution LV customers)              |                                  | <input type="checkbox"/>         |                          |
| (b) Unique definition of customers (this definition should be provided when reporting)             |                                  | <input type="checkbox"/>         |                          |
| Customer-caused events (b) and (c) may both be selected  |                                  |                                  |                          |
| (a) Never counted  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (b) Counted if other customers are affected  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (c) Counted if transmission system failed to protect itself  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (d) Always counted   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| Customer-contracted events (where only the contracted customers are affected)                      |                                  |                                  |                          |
| (a) Events that fall within contracted interruption performance are included in system indices     | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (b) Events that fall within contracted interruption performance are not included in system indices | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (c) Both (a) and (b) are reported separately   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| Lower than standard reliability contracts (where only the contracted customers are affected)       |                                  |                                  |                          |
| (a) Included in system indices   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (b) Not included in system indices   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| Event duration for the purpose of duration measures (SAIRI, SAIDI)                                 |                                  |                                  |                          |
| (a) From inception to restoration of connection point  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (b) From inception to restoration of supply to customers   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (c) Other  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| Time aggregation applied to SAIFI, SAIRI   |                                  |                                  |                          |
| (a) No time aggregation is applied   | <input type="checkbox"/>         | <input type="checkbox"/>         |                          |
| (b) Time aggregation is applied (please specify interval or method used)                           | <input type="checkbox"/> ... min | <input type="checkbox"/> ... min |                          |
| Inclusion of load shed events (i.e. where no disconnection has occurred) if caused by company      |                                  |                                  |                          |
| (a) Included in the calculation of ENS for system minutes,   | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (b) Included in the calculation of frequency and duration  | <input type="checkbox"/>         | <input type="checkbox"/>         | <input type="checkbox"/> |
| (c) Included in the calculation of ENS if exceeds contracted performance                           |                                  |                                  |                          |
| (d) Included in the calculation of frequency and duration if exceeds contracted performance        |                                  |                                  |                          |

()= recommended approach where C4.07 feels that guidance should be provided

### 4.5.3 GENERAL APPLICATION RULES

#### Customer Caused Events

The above indices apply only to transmission-caused events and exclude distribution or customer-caused events. An exception is the case where transmission system equipment did not suitably protect itself (e.g. if a customer fault causes a transmission transformer to fail because the transmission protection did not protect the transformer). A second possible exception is where a customer-caused event causes a transmission system circuit to trip (possibly correctly) and so interrupt supply to a third party. Excluded events should be listed in the reporting.

#### Reliability contracts

Where customers have contracts allowing for a certain number or duration of interruptions per annum, an interruption may be excluded from the calculated indices in cases where only the contracted customers are affected, and the interruption falls within the contracted figures (note that some contracts allow under-frequency load shedding but not load shedding due to overloading of transmission circuits).

As a convention, it is recommended that a 12-month moving method be used to determine which interruptions are included (i.e. the duration and severity of the last interruptions be used).

#### Lower than standard reliability contracts

In some countries a national standard (e.g. grid code rules) or regulatory requirements impose a certain level of reliability, or a standard of connection design to be provided. Where customers have specifically selected lower-than-standard reliability contracts, it may be an option to excluded an interruption from the calculation of indices in cases where only these customers are affected, the interruption falls within the contracted figures, a standard level of reliability would have averted the interruption, and the standard is externally imposed. Such individual cases should be declared when reporting. A problem with this approach is that degradation in performance to these customers is then effectively not reported. A method of overcoming this may be to have dual reporting (i.e. indices calculated with and without these interruptions).

Note that the exclusion of interruptions from system indices based on customer-specific contracts requires information systems to link such events to the contractual conditions.

#### Phases affected

An interruption of one phase on a three-phase system may or may not be counted as an interruption. This should be specified.

### 4.5.4 BENCHMARKING CONSIDERATIONS

Benchmarking interruption performance between companies requires a careful selection of comparable companies (i.e. comparable networks, environmental conditions, geography, customer density etc). It also requires that the method of calculation of indices be identical. Benchmarking interruption performance within one company against historical performance requires consistent calculation methods. Table 41 facilitates alignment of calculation methods.

In order for a company to be able to report according to any of the above indices at any time, it is recommended that the following information be collected for each interruption incident:

- Expected ENS for the event: kWh;
- MW lost;
- Number of connection point interruptions;
- Connection point interruption duration ;
- System minutes per event;
- Number of customers affected (provided by distribution company);
- Customer interruption duration (provided by distribution company).

The following information should be collected for the reporting period (12 months):

- System annual maximum demand for the period;
- Energy delivered for the period;
- Total number of connection points;
- Total number of customers supplied (provided by distribution company).

## 5 RECOMMENDED QUALITY OBJECTIVES

Concerning the objectives or the levels of power quality needed, the situation differs from that of indices because the level of quality is not absolute but it depends on the price clients are willing to pay for it. Optimizing the power quality performance of the electrical system is one of the roles of a system operator. The role of the regulator is to ensure that this is carried out in a cost-effective manner in that if customers expect power quality to be an intrinsic characteristic of the product they also want it at the lowest price. Recognizing that historically the electrical systems in different countries have been designed in different ways to cater for national / regional variations, e.g. different commercial or climatic conditions, it is essential that any set of internationally agreed power quality objectives also recognize these differences.

### 5.1 APPLICATION OF QUALITY OBJECTIVES

#### 5.1.1 NORMAL SYSTEM CONDITIONS

It is recommended that the objectives should apply under normal system operating conditions, unless otherwise specifically agreed in a connection contract. Normal system operating conditions typically exclude:

- a. Conditions arising as a result of a fault or a combination of faults beyond normal security standards;
- b. Exceptional situations and unavoidable circumstances (for example: force majeure, exceptional weather conditions and other natural disasters, acts by public authorities, industrial actions);
- c. Cases where system users significantly exceed their emission limits or do not comply with the connection requirements;
- d. A temporary generator or supply arrangement adopted to keep customers supplied during maintenance or construction work, where otherwise supply would be interrupted.

Normal system operating conditions typically include all generation variations, load variations and reactive compensation states (e.g. shunt capacitor states) when the above exclusions are not in effect, planned system outages and arrangements during maintenance and construction work and normal contingencies under which the system has been designed to operate.

#### 5.1.2 MONITORING

It should be noted that it is not realistic or economical for a system operator to monitor permanently at all supply points. Should the quality objectives be exceeded in such cases, the system operator may need time to investigate and take corrective action.

Power quality monitoring as such simply reflects the situation at a given site or on a supply system as a whole; however it does not tell how much quality degradation is the responsibility of a given party (for example: producers, system operators, end-users, etc.). Even though definite voltage quality indices are measured at a specific connection point on a transmission or distribution system, measured levels are influenced by disturbances originating from all other parts of the system to which this point is interconnected.

Although the obligation for the system operator to provide a given level of quality may be accompanied in part by the obligation for end-users to conform to emission limits, it still remains technically difficult and costly to determine specific responsibilities in case of non-compliance to limits. It is often not feasible to determine how much of the total level of disturbances is the responsibility of a given party. Any such diagnostic task involves intensive and co-ordinated monitoring of currents and voltages at different points of the system, and inevitably can be achieved for campaigns of limited duration. This problem is likely to limit for

a time the practical enforcement of penalties that may be imposed to a system operator in case of non-compliance to voltage quality objectives for harmonics, flicker or unbalance. More research is certainly needed before widely accepted methods for measuring voltage quality can account for specific responsibilities of multiple sources of disturbances.

A limitation of all power quality monitoring surveys is that data is available over a limited number of time for a limited number of locations. For random sampling in a uniform population very strong statistical-mathematical techniques exist to assess the error made by the limitations in space and time. However the location of a power quality monitor is not a random sample from a uniform population. More information is needed on the variation of power quality indices through a system and their variation in time. It is also important that stochastic prediction methods and hybrid statistical/stochastic methods are developed. For harmonics, flicker and unbalance a minimum measurement period of one week is recommended, for voltage dips and interruptions a minimum period of one year is recommended.

## 5.2 HARMONICS

### 5.2.1 RECOMMENDED OBJECTIVES FOR PLANNING LEVELS

The working group recommends to keep the planning levels as they are given in [1] and reproduced in Table 42 below. The corresponding indices are defined in 4.1.1.

| Odd order non-multiple of 3 |                      |                     | Odd order multiple of 3 |                    |        | Even order |                    |        |
|-----------------------------|----------------------|---------------------|-------------------------|--------------------|--------|------------|--------------------|--------|
| Order                       | Harmonic voltage %   |                     | Order                   | Harmonic voltage % |        | Order      | Harmonic voltage % |        |
|                             | MV                   | HV-EHV              |                         | MV                 | HV-EHV |            | MV                 | HV-EHV |
| 5                           | 5                    | 2                   | 3                       | 4                  | 2      | 2          | 1,6                | 1,5    |
| 7                           | 4                    | 2                   | 9                       | 1,2                | 1      | 4          | 1*                 | 1*     |
| 11                          | 3                    | 1,5                 | 15                      | 0,3*               | 0,3*   | 6          | 0,5*               | 0,5*   |
| 13                          | 2,5                  | 1,5                 | 21                      | 0,2 *              | 0,2 *  | 8          | 0,4*               | 0,4*   |
| 17                          | 1,6                  | 1                   | >21                     | 0,2 *              | 0,2 *  | 10         | 0,4*               | 0,4*   |
| 19                          | 1,2                  | 1                   |                         |                    |        | 12         | 0,2*               | 0,2 *  |
| 23                          | 1,2                  | 0,7                 |                         |                    |        | >12        | 0,2 *              | 0,2 *  |
| 25                          | 1,2                  | 0,7                 |                         |                    |        |            |                    |        |
| >25                         | 0,2 +<br>0,5 (25/h)* | 0,2 +<br>0,5 (25/h) |                         |                    |        |            |                    |        |

NOTE: Total harmonic distortion (THD): 6,5% at MV and 3 % at HV. \* see also footnote <sup>6</sup>

**Table 42: Indicative planning levels for harmonics given in [1].**

The reasons for not increasing harmonic planning levels are twofold:

- based on the measurement results given in chapter 3, planning levels are already exceeded at HV-EHV for some dominant harmonics. As a consequence, we should not send the signal that more emissions can be tolerated by increasing the planning levels, otherwise the disturbance levels on the HV-EHV networks would get increasing more and more in the future;
- on the other hand, considering that planning levels are indicative values given as an example in the IEC 61000-3-6; system operators still remain free to adopt different values depending on their network structure and circumstances.

<sup>6</sup> For some higher order harmonics, care must be exercised to specifying very low values such as 0,2% because of practical limitations to measurement accuracy mainly at HV-EHV. Furthermore, a margin depending on system characteristics should exist between MV, HV and EHV planning levels in order to allow coordinating emission of disturbances between different voltage levels.

Where national circumstances make it appropriate, and depending on system characteristics, intermediate levels may be needed between the "MV" and "HV-EHV" planning levels of Table 42, to apply to the lower end of the "HV-EHV" range – this due to the wide range of voltage levels included in HV (35-230 kV). Conversely, an apportioning of planning levels between HV and EHV may also be needed for taking account of the impact on HV systems of disturbing loads connected at EHV, and this may imply in effect the use of planning levels at EHV lower than those above.

## 5.2.2 RECOMMENDED OBJECTIVES FOR VOLTAGE CHARACTERISTICS

For **voltage characteristics**, the existing values for MV are given according to EN 50160 [5] (only dominant odd harmonics are shown in Table 43 below). The table also proposes values for HV-EHV systems, based on measurement results of 3.1 above. The corresponding indices are defined in 4.1.2.1.

| Harmonic order (h) | MV Harmonic Voltage (%) | HV – EHV Harmonic Voltage (%) |
|--------------------|-------------------------|-------------------------------|
| 3                  | 5                       | 2,5                           |
| 5                  | 6                       | 3,0                           |
| 7                  | 5                       | 2,5                           |
| 11                 | 3,5                     | 1,7                           |
| 13                 | 3                       | 1,7                           |
| 17                 | 2                       | 1,2                           |
| 19                 | 1,5                     | 1,2                           |
| 23                 | 1,5                     | 0,8                           |
| 25                 | 1,5                     | 0,8                           |
| THD                | 8                       | 4                             |

**Table 43: Recommended values for voltage characteristics for harmonics at MV-HV-EHV.**

As for the Planning Levels, in the lowest HV voltage range interpolation may be used between the "MV" and "HV-EHV" voltage characteristics in Table 43, and levels may be used for EHV which are lower than those above, to cope with different systems conditions and where national circumstances make it appropriate.

## 5.3 FLICKER

### 5.3.1 RECOMMENDED OBJECTIVES FOR PLANNING LEVELS

In view of high flicker results gathered at HV, the working group recommends setting emission limits by weighting the planning levels at MV, and HV-EHV given in [2] for  $P_{st}$  by taking into account the flicker transfer factor from the source of emissions to the PCC at EHV, HV, MV and LV. To enable this, the system operator has to evaluate the flicker transfer factor for various operating conditions of the system. The corresponding indices for  $P_{st}$  are given in 4.2.1.

|          | Planning levels |          |
|----------|-----------------|----------|
|          | MV              | HV - EHV |
| $P_{st}$ | 0.9             | 0.8      |

**Table 44: Recommended values for planning levels for flicker at MV-HV-EHV.**

Furthermore, considering the technical and cost implications of meeting flicker requirements for utilities and system users, JWG C4.07 recommends that further study be undertaken in order to analyze in detail

the reasons why high flicker levels, up to twice the compatibility levels, are reported mainly at HV-EHV without known problems. Aspects to be analyzed include:

- Time of the day or night when high flicker levels occur (e.g.: weight daylight hours less severely);
- Influence of sensitivity to flicker of the new type of lighting in use [43];
- Transfer factors between different voltage levels.

#### 5.3.1.1 Assessment of flicker transfer coefficients

The transfer coefficient of flicker between two points A and B is defined as the ratio of the  $P_{st}$  values, measured at the same time in both locations.

$$T_{P_{st}AB} = P_{st}(B) / P_{st}(A)$$

This concept is useful in practice, in the assessment procedure of emission limits for fluctuating loads in MV and HV power systems:

- when assessing limits for HV fluctuating loads, the possible allowance for higher HV emission levels must rely on a good knowledge of the flicker transfer coefficient from the upstream HV system to the LV distribution networks (where the sensitive loads, i.e. lighting loads, are connected).
- when assessing limits for MV fluctuating loads, one considers usually that the flicker level in the MV system results from the combination of the flicker coming from the upstream HV system and the flicker resulting from all fluctuating loads connected to the MV system. The transfer coefficient from HV to MV must be known, in order to assess correctly the contribution of the HV loads and the allowed global contribution of the local MV loads.

From various measurement campaigns, it appears that the flicker produced at EHV or HV sometimes significantly attenuates in the MV or LV networks. This reduction is mainly due to the presence of motor loads in these networks.

#### Application Example

Synchronous flicker measurements have been carried out in order to obtain experimental values for transfer coefficients between various voltage levels. Measurements were carried out on 220 kV, 70 kV and at 15 kV, both substations are 13 km distant and connected through a 70 kV overhead line. The 220 kV point is the point of common coupling with several large arc furnaces.

##### Flicker Transfer from 220 kV to 70 kV:

There is an excellent correlation between 220 kV and 70 kV  $P_{st}$  values. The transfer coefficient from 220 kV to 70 kV equals 0,82.

##### Flicker Transfer from 70 kV to 15 kV:

There is also a very good correlation between 70 kV and 15 kV  $P_{st}$  values. The transfer coefficient from 70 kV to 15 kV equals 0,91.

##### Flicker Transfer from 15 kV to 230 V:

Even the transfer coefficient between 15 kV and 230 V has been calculated. Here, the global correlation is less good, due to many local 230 V flicker sources. Despite this problem, a flicker transfer coefficient can be calculated for each combination of  $P_{st}$ -values (15 kV and 230 V) if the 230 V  $P_{st}$  values are small. In

these cases, flicker sources at 15 kV are the only ones with influence, and a transfer coefficient between 0,98 and 1,0 was calculated from there to 230 V.

When the ratio of  $P_{st-15\text{ kV}}$  and  $P_{st-70\text{ kV}}$  becomes greater than 1, this means that the 15 kV-flicker sources dominate, and these values can not be taken into account for the determination of the transfer coefficient.

Because no permanent fluctuating loads were connected to the 15 kV network, the long term flicker  $P_{lt}$  is smoothed by the filtering effect caused by the averaging process. Thus, the  $P_{lt}$  transfer coefficient from 70 kV to 15 kV could also be calculated, and equals 0.92, which follows the short term transfer coefficient.

| Voltage level        | $T_{P_{stAB}}$ |
|----------------------|----------------|
| 220 kV towards 70 kV | 0.82           |
| 70 kV towards 15 kV  | 0.91           |
| 15 kV towards 230 V  | 0.98 – 1.00    |

**Table 45: Example of Flicker Transfer coefficients.**

### General observations

Following observations can be made:

- no significant reduction is found from 15 kV to 230 V; other measurement campaigns gave also transfer coefficients close to unity.
- The major flicker reduction is observed between the 220 kV and 70 kV levels (about 0,8) and to a less extent between 70 kV and 15 kV levels (about 0,9), leading to a total transfer coefficient from 220 kV to 15 kV of about 0,72.
- Similar results are obtained for  $P_{lt}$ .
- Except when a very good correlation exists between all the measured values on different voltage levels, the assessment of the transfer coefficient from the ratio of statistical indices (such as 99% or 95% percentiles) would produce erroneous results. This is the case when significant flicker sources are present at the lower voltage level. It is then preferable to eliminate the highest flicker values and estimate the transfer coefficient from the correlation between the lowest ones and the corresponding values on the higher voltage level, or by network analysis methods.

### 5.3.2 RECOMMENDED OBJECTIVES FOR VOLTAGE CHARACTERISTICS

Similarly to planning levels, voltage characteristics for flicker at HV-EHV may be obtained by dividing the flicker value at LV given in [5] by the transfer factor between EHV, HV, MV and LV. The indications given in the previous section also apply for assessing the flicker transfer factor. The corresponding indices are given in 4.2.2.1.

## 5.4 UNBALANCE

### 5.4.1 RECOMMENDED OBJECTIVES FOR PLANNING LEVELS

Considering the current practices in many countries and the measurement results, the WG recommends the following objectives for voltage unbalance planning levels. The corresponding indices are defined in 4.3.1.

| Voltage level | Planning Level<br>$U_{neg}$ (%) |
|---------------|---------------------------------|
| MV            | 2                               |
| HV            | 1,5%                            |
| EHV           | 1%                              |

**Table 46: Recommended values for planning levels for voltage unbalance at MV-HV-EHV.**

#### 5.4.2 RECOMMENDED OBJECTIVES FOR VOLTAGE CHARACTERISTICS

Considering existing standard EN 50160 for MV and the measurement results for HV - EHV, the WG recommends, applied to the 95% weekly value of  $U_{neg,sh}$ , objectives for unbalance voltage characteristics are given below. The corresponding indices are defined in 4.3.2.1.

| Voltage level  | Voltage characteristics<br>$U_{neg}$ (%) |
|--|--|
| MV   | 2% <small>see note</small>               |
| HV   | 2%                                       |
| EHV  | 1,5%                                     |
| Note: In some areas, unbalances up to 3% may occur in cases where predominantly single-phase loads are supplied. |  |

**Table 47: Recommended values for voltage characteristics for voltage unbalance at MV-HV-EHV.**

## 5.5 VOLTAGE DIPS

Objectives for site indices cannot be given due to the very large difference between the number of voltage dips to be expected at different sites, so at this stage, it is not possible to give appropriate objective values for any of the voltage-dip indices.

Year-to-year comparison of the values of site indices for one site may be used to see trends in the voltage quality of a particular site, although the trends may be masked by random statistical variations or weather variations between years. Comparison for different sites is not recommended except as an aid in the choice of a suitable location for an installation containing sensitive equipment. Indices can only be used to identify typical levels of disturbances for different types of sites and as such a feedback for improvements towards the network operator.

## 5.6 LONG INTERRUPTIONS

The benchmarking of transmission interruption performance is complicated by the combination of unique influencing factors in each country (geography, environmental conditions, load density, location of generation sources, degree of excess capacity, network topology, system voltage levels). The dominant benchmarking approach for Transmission companies is therefore based on historical performance of the company itself.

Objectives for site or system indices cannot be given due to the large difference in network topologies and operational conditions. Use of the proposed indices will facilitate future benchmarking of utilities that have similar networks and operating environments.

## 6 CONCLUSIONS AND OTHER RECOMMENDATIONS

**For steady state disturbances, such as harmonics, flicker and unbalance**, two categories of indices can be distinguished given their use:

- **Indices for planning levels:** internal quality objectives;
- **Indices for voltage characteristics:** external reporting system performance.

In reporting voltage characteristics, two level of indices can also be distinguished:

- **Site indices:** the performance at a specific site;
- **System indices:** the performance of a system.

Recommended indices for planning levels are similar to those given in IEC 61000-3-6 and 61000-3-7 with the difference that one or more of the recommended indices can be used. Maximum values are not recommended however due to the possibility of their being inflated by transients (instead 99% values may be used). In the case of flicker, 10-min values should be sufficient for planning purposes. Because of the similarity of effects caused by harmonics and voltage unbalance (thermal effects) the working group recommends using similar indices for both.

For voltage characteristics/site indices, considering practical reasons such as allowing easy comparison of voltage characteristics between LV-MV and HV-EHV and also for having common monitoring methods, the WG recommends indices for HV-EHV that are similar to those given in EN 50160.

The recommended system index is the value of the site index not exceeded for a high-percentage of sites, for each individual index and parameter. Examples of high-percentile sites are 90, 95 and 99%. The choice of the percentage of sites for the system index a matter of agreement between the system operator and the regulator.

Objectives for planning levels are similar to those already given in IEC 61000-3-6 and IEC 61000-3-7 for harmonics and flicker. For flicker, it is also recommended to weight the planning levels at HV-EHV by taking into account the transfer coefficient between EHV, HV, MV and LV where flicker sensitive lighting equipment is connected. It is noted that planning levels should remain indicative values that can be adapted to different system characteristics and circumstances.

Objectives recommended for voltage characteristics at HV-EHV are primarily based on the measurement results collected by the WG and summarized in chapter 3. For instance, for 5<sup>th</sup> harmonic voltage characteristic at HV-EHV a value of 3% is recommended as most surveys showed results between 2,5% and 3%.

**For voltage dips**, the basic characteristics are the retained voltage and the duration for each dip and it is recommended to calculate these according to IEC 61000-4-30. Site indices can be presented in a number of different ways as in the form of a voltage-dip table, as a contour chart, using SARFI indices, etc. Other details of the characterisation method used, such as the reference voltage to calculate the remaining voltage, the time and phase aggregation method, etc., should be declared. Detailed indications are also given on time aggregation methods.

Voltage dips system indices can be calculated from the value not exceeded by a high percentage of sites (ex.95% of sites) the actual percentage of sites is to be agreed with the system operator. Weighting factors can be introduced to take into account the sites not monitored and the difference in importance between different sites. It is also recommended, particularly at HV-EHV, and in non-solidly earthed systems, that

voltage dips measurements use the phase-to-phase voltages which give an image that is closer to what the end-users equipment see.

At this stage, it not possible to give appropriate objective values for any of the voltage-dip indices. Indices can only be used to identify typical levels of disturbances for different types of sites and as such a feedback for improvements towards the network operator.

**For long interruption indices**, recommendations for MV systems are to refer to IEEE 1366 which recommends indices such as SAIFI, MAIFI, SAIDI, CAIDI.

And for HV-EHV transmission systems, three categories of interruption indices are presented in order to take into consideration different reporting requirements describing different aspects of interruption performance, i.e:

- Connection Point Interruption Performance (CPI);
- End-Customer Load Interruption Performance (CLI);
- System Interrupted Energy Performance.

It is generally recommended that companies select one of the three philosophies for system reporting purposes and use the set of indices defined for the selected philosophy.

The first philosophy is addressing the need, in fully liberalised electricity markets, for the interruption performance of a transmission company to be described and reported separately from the (negative or positive) impact of the networks on its customers. *Connection point interruption indices* address this aspect by describing the reliability and availability of all individual interfaces between the transmission system and the networks of its various customers.

The second philosophy is addressing the need for transmission system reporting performance on the same basis as often used by distribution system operators. Thus *End-customer interruption performance indices* describe the reliability of the supply for transmission-caused events to actual end customers (i.e. taking into consideration the effect of the underlying distribution system). This requires information from Distribution customers on the number of customers affected, and the duration (particularly in the case of stepped restoration).

The third philosophy is actually similar to the second one in that the actual impact on *end-customer interruption* indices is approximated using the estimated energy not supplied (EENS in MWh) and the size of the load interrupted (MW), so avoiding the need to gather detailed information about the distribution customers.

Objectives for long interruptions for site or system indices cannot be given due to the large difference in network topologies (radial vs. meshed, location of generators) and operational conditions (environment, geography). The dominant benchmarking approach for Transmission companies is therefore based on historical performance of the company itself. Use of the proposed indices will facilitate future benchmarking of utilities that have similar networks and operating environments.

Finally, this report should also send a message to equipment manufacturers to provide monitoring equipment able to measure the different power quality indices recommended in this report, in particular the need to calculate daily and weekly percentile values from 3-second or 10-minute values, without necessarily storing unmanageable quantities of raw data. It is equally important that monitoring equipment integrates the flagging concept introduced in the recent IEC 61000-4-30.

**ANNEX A.: SCOPE OF Cigré WG C4.07/Cired (36.07)**

Study Committee No : 36

**WORKING GROUP\* FORM**

WG\* No: 36-07

Name of Convener: Germain BEAULIEU (CA)

Title of the Group : POWER QUALITY INDICES AND OBJECTIVES

Scope, deliverables and proposed time schedule of the Group :

The new CIGRE WG 36.07 would aim at recommending Power Quality Indices and Objectives, Le. helping the new Transmission System Operators (TSOs) in one of their major responsibilities :

- The primary motivation would be to analyze the return of experience three years after the publication of IEC 61000-3-6/7 (not the procedure to determine the emission limits, but the base of the limits, Le. the quality targets - which are called "planning levels" - and the associated quality indices) : are the quality indices chosen for harmonics, interharmonics and flicker suitable ? are the suggested values for planning levels suitable? may the same approach be extended to voltage unbalance ?
- Part of the study would be to collect information on actual levels of harmonics, flicker and unbalance, from LV up to HV systems (data requested by IEC ; cooperation needed with CIREN).
- Another aspect could be studied, in relation with EN 50160 (a European standard concerning LV and MV systems) : may the EN 50160 approach be extended to HV systems ? if yes, what should be the target values - which are called "voltage characteristics" - in HV ?
- A reason to create a new WG for the task is the need to have representatives of SOs (System Operators) in the group ; this does not prevent of course the interest to have also representatives of R&D or engineering companies (typically the profile of 36.05 members) ; representatives of other players of the liberalized market (producers, suppliers, manufacturers) would also be valuable.
- 36.07 would also be the adequate forum to discuss the report "Recommendations for Tabulating RMS Variation Disturbances with Specific Reference to Utility Power Contracts" (mentioned in the 1998 Progress Report of WG 36-05, based on recent work by EPRI and IEEE), so that a close cooperation between 36.05 and 36.07 will be highly desirable.

The WG would aim at delivering some important products

- recommended internal quality objectives (planning levels), enabling to, determine emission limits for disturbing installations ;
- recommended external quality objectives (voltage characteristics), to be presented to regulators and system users ;
- a message for the manufacturers of quality monitoring instruments : we need instruments which fulfil the requirements of the future IEC 61000-4-30 and which can easily give us the quality indices related to the above objectives.

The duration of this WG should be some 2-3 years.

**Approval by TC Chairman :**

**Date :** 11 JUL 2000

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\* or Study Committee Task Force (SCTF)

## **ANNEX B: Detailed Measurement Results Gathered by WG C4.07 :**

The detailed measurement results gathered by Cigré-Cired JWG C4.07 can be found in the following document:

**Annex\_B\_Detailed\_Measurement\_Data\_Final.doc**

Annex B file is to be joined to the main report.

## ANNEX C: Checklist for the calculation of voltage-dip indices.

### General survey information

#### 1. Calculation of single-event characteristics and indices

Monitor connection [PP] \_\_\_\_\_

RMS voltage

RMS calculation window [1 cycle]: \_\_\_\_\_

Refreshment of RMS calculation [ $\frac{1}{2}$  cycle]: \_\_\_\_\_

Retained voltage

Way of calculation [lowest value]: \_\_\_\_\_

Three phases [lowest value]: \_\_\_\_\_

Duration

Way of calculation [time below threshold]: \_\_\_\_\_

Starting threshold [90%]: \_\_\_\_\_

Ending threshold [90%]: \_\_\_\_\_

Fixed threshold

Reference value in kV: \_\_\_\_\_

Sliding-reference threshold

Method used [1-minute filter]: \_\_\_\_\_

Three phases [from first beginning to last end]: \_\_\_\_\_

Voltage-sag energy

Calculated from rms values

Calculated from retained voltage and duration

Threshold value: [90% of nominal]: \_\_\_\_\_

Maximum value used [None]: \_\_\_\_\_

Short interruptions included [No]: \_\_\_\_\_

Voltage-sag severity

Reference curve used [SEMI]: \_\_\_\_\_

Threshold value: [90% of nominal]: \_\_\_\_\_

#### 2. Calculation of site indices

SARFI-X

Maximum duration [1 minute]: \_\_\_\_\_

Minimum retained voltage [none]: \_\_\_\_\_

X value used [10, 40, 70, 85, 90]: \_\_\_\_\_

SARFI-Curve

Reference curve used: \_\_\_\_\_

Maximum duration [1 minute]: \_\_\_\_\_

Voltage-sag table

Type of table used: \_\_\_\_\_

Treatment of borderline cases [most severe cell]: \_\_\_\_\_

 Voltage-sag energy

Lowest retained voltage [Yes]: \_\_\_\_\_

Maximum duration [1 minute]: \_\_\_\_\_

 Voltage-sag severity

Lowest retained voltage [Yes]: \_\_\_\_\_

Maximum duration [1 minute]: \_\_\_\_\_

 Time aggregation for very-close events

Maximum separation: \_\_\_\_\_

Calculation of separation [end of first event to start of next event]: \_\_\_\_\_

Retained voltage [lowest of the individual events]: \_\_\_\_\_

Duration [sum of the individual events]: \_\_\_\_\_

 Time aggregation for close events

Maximum separation: \_\_\_\_\_

Calculation of separation [end of first event to start of next event]: \_\_\_\_\_

Retained voltage [lowest of the individual events]: \_\_\_\_\_

Duration [longest of the individual events]: \_\_\_\_\_

 Spatial aggregation

Method used: \_\_\_\_\_

 Correction for monitor unavailability

Method used: \_\_\_\_\_

**3. Calculation of system indices**

Number of sites monitored: \_\_\_\_\_

Percentage of total number of sites: \_\_\_\_\_

Method used to select monitored sites: \_\_\_\_\_

 Average of the site indices:

Method used to determine weighting factors

 95-percentile site

Method used to determine weighting factors

 50-percentile site

Method used to determine weighting factors

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