# Power quality standard comparison between China, IEEE, and IEC

by

Tianxu Zheng

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Electrical and computer Engineering

Auburn, Alabama
December 15, 2018

Key words: power quality, standard,
harmonics, flicker, distributed resources



Approved by

Mark Halpin, Chair , Professor, Electrical and Computer Engineering
John Y.Hung, Professor, Electrical and Computer Engineering
Robert Nelms, Professor, Electrical and Computer Engineering

Abstract

This thesis compares power quality standards and measurement methods of the U.S. and China. These standards specify the power quality parameters (harmonics, flicker, unbalance,etc.), that are dedicated to ensure the safety and normal operation of the whole power system. But some instructions, limits, or coefficients vary between these two countries. These differences occur on many parts of the whole power system, such as power producers, including the big power plants, distributed generators, and power consumers, which include users like factories, businesses, residential users, and other auxiliary equipment. Meanwhile, due to the globalization of the world, some standards in this industry are going to be consistent. This project talks about the similarities and differences in these regions, and some of the governing reasons.

## Acknowledgments

I would like to express my gratitude to my supervisor, Dr. Mark Halpin, who gives direction and motivation to me to complete the research. He taught me step by step how to complete a paper in a standardized language. Without his help, this paper could not be completed. Also, his clear and methodical talk in class in the power region inspired my studying interest.

I also would like to thank my uncle, Bohong Liang for some documents he gave me from China. That saved me a lot of time in research.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

| | |
|---|---|
| IEEE | Institute of Electrical and Electronics Engineers |
| IEC | International Electrotechnical Commission |
| GB | Chinese National Standard (transliteration) |
| GB/T | Chinese National Recommended Standard (transliteration) |
| GB/Z | Chinese Guidance Standard Document (transliteration) |
| ANSI | American National Standards Institute |
| SCR | Short Circuit Ratio |
| PCC | Point of Common Coupling |
| THD | Total Harmonic Distortion |
| HR | Harmonic Ratio |
| RMS | Root Mean Square |
| DG | Distributed Generators |
| DR | Distributed Resources |
| EPS | Electric Power System |
| PV | Photovoltaic |
| TRD | Total Rated Distortion |
| THC | total harmonic current |
| PWHC | partial weighted harmonic current |
| LV | Low Voltage |

| | |
|---|---|
| MV | Medium Voltage |
| HV | High Voltage |
| EHV | Extra High Voltage |

# CHAPTER 1. INTRODUCTION

Power quality issues now get more and more attention from utility companies and power consumers, and they have become one of the most concentrated areas in the power industry. Power quality has become an important concept, including various types of power interference. The general meaning of power quality is “any equipment fault or abnormal state caused by voltage, current, or frequency deviation”[1].

The reason to care about power quality originally was the economic value. Industrial consumers are directly effected by power quality issues. Compared to the traditional facilities, a large amount of automation and artificial intelligent (AI) equipment is more sensitive to the quality of the power supplied. Poor power quality can cause production halts or even equipment failure. Residents are also typical representatives who are affected by power quality problems.

“Power quality” is also “voltage quality” to some extent. The power over time is the energy transmitted by the system, and it is hard to limit the “power” quality. In fact, the power system can only control the voltage. Of course, there is a relationship between voltage and current in the same system. So, when focusing on a voltage issue, we also need to assess the current to satisfy the user’s requirement for sufficient power quality.

# CHAPTER 2. POWER QUALITY ISSUES

## Ⅰ Classification

Power quality issues are sets of problems of different kinds. Harmonics, flicker (voltage fluctuations), voltage dips, sags, interruptions, swells, and voltage imbalance are the main problems of power quality. Harmonics, flicker (voltage fluctuations), and voltage imbalance are the topics that are discussed thoroughly in this thesis with particular emphasis on the standards that have been developed in China and by the International Electrotechnical Commission (IEC) and the Institute for Electrical and Electronic Engineers (IEEE).

## Ⅱ Rationale

### 1. Harmonics.

Harmonics are caused by nonlinear equipment in the power system. The current is not a linear function of the voltage given. So, even if the terminal voltage of the equipment is given as a pure sinusoidal wave, the current can be distorted. Actually, any periodic distortion can be expressed as a sum of a set of sinusoidal functions. The frequency of each term is an integer multiple of the fundamental frequency. Any term except the one with fundamental frequency is called a harmonic as shown in Figure 2.1.

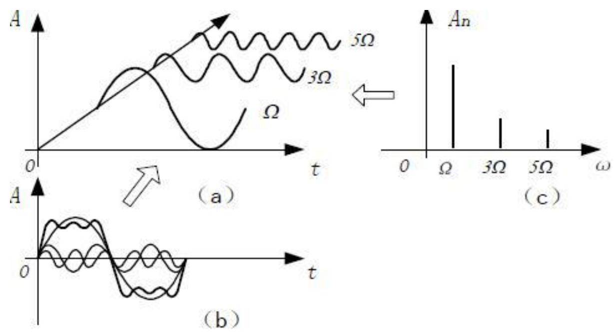


Figure. 2.1 Spectrum of Any Periodic Signal

Distorted power system voltages and currents can be written out as a sum of pure sinusoids called a Fourier series as shown in Figure 2.2. This procedure can be done using the Fourier series.

$$
\begin{aligned}
f(t) = & F_0 \\
& + \sqrt{2}F_1 \cos(\omega_0 t + \theta_1) \\
& + \sqrt{2}F_2 \cos(2\omega_0 t + \theta_2) \\
& + \cdots \\
& + \sqrt{2}F_\infty \cos(\infty\omega_0 t + \theta_\infty) \\
= & F_0 + \sum_{n=1}^{\infty} \sqrt{2}F_n \cos(n\omega_0 t + \theta_n)
\end{aligned}
$$

Fundamental wave

Harmonics

Figure. 2.2 Fourier Series

**2. Voltage imbalance**

Symmetrical components is the most useful method to describe voltage imbalance. Any set of three-phase quantities can be written as an equivalent set of “symmetrical components” as shown in Figure 2.3.

$$\begin{bmatrix} \overline{F}_a \\ \overline{F}_b \\ \overline{F}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \overline{a}^2 & \overline{a} \\ 1 & \overline{a} & \overline{a}^2 \end{bmatrix} \begin{bmatrix} \overline{F}_0 \\ \overline{F}_1 \\ \overline{F}_2 \end{bmatrix}$$

$$\overline{a} = 1\angle 120^\circ$$

Figure 2.3 Relationship Between Phase Variables and Sequence Variables

In Figure 2.3, $\overline{F}_a, \overline{F}_b, \overline{F}_c$ are the phase variables, and $\overline{F}_0$ (zero sequence), $\overline{F}_1$ (positive sequence), and $\overline{F}_2$ (negative sequence) are the sequence quantities. Each sequence quantity represents a set of phasor variables as follows:

$\overline{F}_1$: a balanced “abc” set of phasors;

$\overline{F}_2$: a balanced “cba” set of phasors; and

$\overline{F}_0$: a- set of three equal phasors.

If the system is completely balanced and has positive phase sequence, $\overline{F}_1$ should be equal to the phase variables in magnitude and phase, while $\overline{F}_2$ and $\overline{F}_0$ should be 0. On the contrary, if the system is more unbalanced, the negative and zero sequence variables will be larger. An example is given to show how symmetrical component is used.

Determine the sequence voltage for the following set of phase variable voltages:

$V_{an} = 277\angle -5^\circ V$ , $V_{bn} = 285\angle 116^\circ V$ , $V_{cn} = 277\angle -127^\circ V$ .

$$\begin{bmatrix} 277\angle -5^\circ \\ 285\angle 116^\circ \\ 277\angle 127^\circ \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0.814 - j0.581 & 0.814 + j0.581 \\ 1 & 0.814 + j0.581 & 0.814 - j0.581 \end{bmatrix} \begin{bmatrix} \overline{F}_0 \\ \overline{F}_1 \\ \overline{F}_2 \end{bmatrix}$$

$$\begin{bmatrix} \overline{F_0} \\ \overline{F_1} \\ \overline{F_2} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0.814 - j0.581 & 0.814 + j0.581 \\ 1 & 0.814 + j0.581 & 0.814 - j0.581 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 277\angle -5^\circ \\ 285\angle 116^\circ \\ 277\angle 127^\circ \end{bmatrix} = \begin{bmatrix} 6.35\angle 145.5^\circ \\ 3.32\angle -33.1^\circ \\ 279.6\angle -5.3^\circ \end{bmatrix}$$

From the answer we can see that this system is a “cba” sequence of phasors with some interference caused by positive and zero sequence.

## 3. Flicker

In order to quantify the definition of flicker, voltage fluctuation needs to be discussed first. Voltage fluctuation is defined as a series of relatively rapid changes in the voltage RMS value. This voltage fluctuation phenomenon may occur frequently during power system operation, and the change process may be regular (such as daily capacitor switching) or irregular (such as fault occurs). The change period is generally greater than the power frequency period. In order to describe the characteristics of a voltage that fluctuates greatly in a short time, the change between two adjacent extreme values among a series of voltage fluctuations is referred to as a primary voltage fluctuation.

Voltage fluctuations can be described by the difference between two extreme values of a series of RMS values, the percentage of which is expressed as shown in (2-1).

$$d = \frac{\Delta U}{U_N} \times 100\% \qquad (2\text{-}1)$$

In (2-1), the following definitions apply:

$\Delta U$ is the variation of voltage amplitude in a specific period of time; and

$U_N$ is the voltage level.

The causes of voltage fluctuations are diverse and usually include:

1) Short circuit faults and switching operations in the power distribution system;

2) Use of reactive power compensation devices; and

2) Switching or operation of large equipment.

Voltage fluctuations can cause some electrical equipment to malfunction. In lighting equipment for commercial and residential buildings, incandescent lamps account for a large portion, and fluctuations in voltage can cause significant flashing of incandescent lamps which is unbearable in severe cases. Therefore, the light output of the incandescent lamp is selected as the basis for judging whether a voltage fluctuation value can be accepted. This is generally refered to as flicker and the definition of the flicker is:

*Flicker:* A directly visible change in brightness of a light source which can be due to fluctuations of the light source itself, or due to external causes such as due to rapid fluctuations in the voltage of the power supply (power-line flicker) or incompatibility with an external dimmer [1].

There are two types of flicker. One is caused by periodic voltage fluctuations, called periodic voltage flicker, and the other one is caused by occasional or random voltage changes, called non-periodic flicker.Whether a voltage fluctuation can cause visible flicker depends on the following factors:

1) Potential flicker source's capability;

2) System impedance; and

3) Fluctuation frequency.

Flicker is usually measured by a flicker meter that is specified by the IEC and also adopted by the IEEE [2].

# CHAPTER 3. POWER QUALITY STANDARD COMPARISON

## Ⅰ Introduction of the Three Groups of Standards

Chinese national standards are divided into mandatory national standards (GB) and recommended national standards (GB/T). GB refers to a national mandatory standard and must be implemented. Products that do not meet mandatory standards are prohibited from being produced, sold or imported. GB/T refers to recommended national standards (GB/T). The recommended national standards refer to national standards that are voluntarily adopted through economic means or market regulation in terms of production, exchange, and use. Any company of this type has the right to decide whether to adopt them. Violation of such standards does not assume economic or legal responsibility. However, once accepted and adopted, or agreed by the parties to be included in the economic contract, it becomes a technical basis that all parties must abide by and is legally binding.

The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) is an organization within IEEE that develops global standards in a broad range of industries including power and energy, information technology, communications, health care, and many more. The IEEE Standards Association now is the world's leading standards-setting body in electrical engineering. The IEEE Standards Association has established strategic partnerships with a number of international standards organizations, including the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the International Telecommunications Union (ITU). Nowadays, in the power quality portion of the US power industry, companies generally adopt IEEE related standards.

The International Electrotechnical Commission (IEC) is the world's first non-governmental international electrical standardization body. After the establishment of the ISO in 1947, IEC was incorporated into ISO as an institution, but it remained technically and financially independent. According to the 1976 agreement between ISO and IEC , both organizations are legally independent organizations. IEC is responsible for international standardization work in the electrical, electronic and their application areas . The IEC member countries include the vast majority of industrially developed countries and some developing countries. The purposes of the IEC are to promote the international unification of electrical standards, to advance international cooperation in standardization related to the fields of electrical and electronic engineering, and to enhance mutual understanding among the international community. To achieve these goals, various publications including international standards are published. It is hoped that national committees will use these international standards if their national conditions permit. IEC's areas of work include electrical, telecommunications and atomic energy. The IEC currently has 81 member countries (60 full members and 21 associate members), and this group is known as the IEC National Committee.

## Ⅱ Harmonics standards

1. Chinese standard

GB/T 14549-93 is the harmonics standard currently used in China, and it was published in 1993. The standard stipulates the harmonic limits for the public power grids and specifies the

the testing methods. GB/T 14549-93 is not a compulsory standard, however, but is an effective planning reference standard. Table 3.1 gives the harmonic limits for the voltage (line to neutral) of public power grids.

Table 3.1 Voltage Harmonics Limits

| Voltage class (kV) | THD% | HR of each order of harmonics% | |
|---|---|---|---|
| | | Odd harmonics | Even harmonics |
| 0.38 | 5 | 4 | 2 |
| 6<br>10 | 4 | 3.2 | 1.6 |
| 35<br>66 | 3 | 2.4 | 1.2 |
| 110 | 2 | 1.6 | 0.8 |

Here, THD (total harmonic distortion) can be represented as shown in (3-1).

$$THD_{\mathrm{v}} = \frac{\sqrt{\sum_{h=2}^{n}(U_h)^2}}{U_1} \times 100(\%) \tag{3-1}$$

Note: The order of harmonics measured is usually 2 to 19.

Harmonic ratio of a harmonic voltage ( $HRU_h$ ) can be expressed as shown in (3-2), where $U_1$ is the fundamental term of the voltage (RMS value) and $U_h$ is the RMS voltage at harmonic *h*.

$$HRU_{\mathrm{h}} = \frac{U_h}{U_1} \times 100(\%) \tag{3-2}$$

Table 3.2 shows the limits for the currents flowing into the power grid. It stipulates that all the user's harmonic currents (RMS value) which flow into the PCC node should not exceed the numbers in Table 3.3. The relationship between harmonic current and $HRU_{\mathrm{h}}$ is shown in (3-3).

$$HRU_h = \frac{\sqrt{3}Z_h \cdot I_h}{10 \cdot U_N}(\%) \tag{3-3}$$

An approximate calculation equation can be used in industrial applications as shown in (3-4) or as shown in (3-5) based on the assumption that $Z_h = \frac{U_N^2}{S_k} \cdot h$.

$$HRU_h = \frac{\sqrt{3}U_N \cdot h \cdot I_h}{10S_k}(\%) \tag{3-4}$$

$$I_\mathrm{h} = \frac{10 \cdot S_\mathrm{k} \cdot HRU_\mathrm{h}}{\sqrt{3} \cdot U_N \cdot \mathrm{h}}(\%) \tag{3-5}$$

In (3-3)-(3-5),

$U_N$ is the voltage level of power grid;

$S_\mathrm{k}$ is the three phase short circuit capacity;

$I_h$ is the h order's harmonic current; and

$Z_h$ is the h order's harmonic impedance of the system.

At the point of common coupling (PCC), each user's harmonic limit value is determined according to the ratio of the user's load demand capacity and the total capacity as shown in (3-6) where

$I_h$ is the current limit value of the PCC node in Amperes;

$S_i$ is the load demand capacity of the $i^{th}$ user in MVA;

$S_t$ is the power supply capacity of the PCC in MVA; and

$\alpha$ is the phase superposition coefficient with the appropriate values in Table 3.3:

$$I_{hi} = I_h (S_i / S_t)^{1/\alpha} \tag{3-6}$$

$S_{ki}$

Table 3.2 Chinese Harmonic Current Limits

| Nominal voltage (kV) | Short circuit capacity (MVA) | Harmonic order and its limitation value(A) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| 0.38 | 10 | 78 | 62 | 39 | 62 | 26 | 44 | 19 | 21 | 16 | 28 | 13 | 24 | 11 | 12 | 9.7 | 18 | 8.6 | 16 | 7.8 | 8.9 | 7.1 | 14 | 6.5 | 12 |
| 6 | 100 | 43 | 34 | 21 | 34 | 14 | 24 | 11 | 11 | 8.5 | 16 | 7.1 | 13 | 6.1 | 6.8 | 5.3 | 10 | 4.7 | 9.0 | 4.3 | 4.9 | 3.9 | 7.4 | 3.6 | 6.8 |
| 10 | 100 | 26 | 20 | 13 | 20 | 8.5 | 15 | 6.4 | 6.8 | 5.1 | 9.3 | 4.3 | 7.9 | 3.7 | 4.1 | 3.2 | 6.0 | 2.8 | 5.4 | 2.6 | 2.9 | 2.3 | 4.5 | 2.1 | 4.1 |
| 35 | 250 | 15 | 12 | 7.7 | 12 | 5.1 | 8.8 | 3.8 | 4.1 | 3.1 | 5.6 | 2.6 | 4.7 | 2.2 | 2.5 | 1.9 | 3.6 | 1.7 | 3.2 | 1.5 | 1.8 | 1.4 | 2.7 | 1.3 | 2.5 |
| 66 | 500 | 16 | 13 | 8.1 | 13 | 5.4 | 9.3 | 4.1 | 4.3 | 3.3 | 5.9 | 2.7 | 5.0 | 2.3 | 2.6 | 2.0 | 3.8 | 1.8 | 3.4 | 1.6 | 1.9 | 1.5 | 2.8 | 1.4 | 2.6 |
| 110 | 750 | 12 | 9.6 | 6.0 | 9.6 | 4.0 | 6.8 | 3.0 | 3.2 | 2.4 | 4.3 | 2.0 | 3.7 | 1.7 | 1.9 | 1.5 | 2.8 | 1.3 | 2.5 | 1.2 | 1.4 | 1.1 | 2.1 | 1.0 | 1.9 |

Table 3.3 Phase Superposition Coefficient

| h | 3 | 5 | 7 |
|---|---|---|---|
| $\alpha$ | 1.1 | 1.2 | 1.4 |
| h | 11 | 13 | 9,>13,or any even number |
| $\alpha$ | 1.8 | 1.9 | 2 |

When the short-circuit capacity of the common connection point is different from the reference short-circuit capacity given in Table 3.2, the allowable value of the harmonic current is corrected according to (3-7) where

$I_h$ is the current limit of the $h^{th}$ harmonic when the short circuit capacity is $S_{ki}$;

$S_{ki}$ is the short circuit capacity of the busbar;

$I_{hp}$ is the current limit of the $h^{th}$ harmonic in Table 3.3; and

$S_k$ is the reference short-circuit capacity.

$$I_h = \frac{S_{ki}}{S_k} \cdot I_{hp} \tag{3-7}$$

There are not any differences between power consuming facilities (users) and power producing facilities (generators) in power quality issues in China. But China implements some standards for new energy power sources that connect to the power grid. These standards vary from the the standards used in U.S.. This will be discussed in the next chapter. The harmonic emission limit for any equipment in China is the same as the relevant IEC standards for equipment, which will be discussed in part 3 [3].

2. The standard used in U.S.

In order to make limit indices representative, simple, and easy to measure, IEEE uses various quantities to evaluate harmonic levels. They are:

1) Individual harmonic and total voltage harmonic distortion and

2) Individual harmonic and total current harmonic distortion.

The concepts for developing harmonic limits in IEEE are:

1) Limit harmonic current injections from individual customers so that they do not cause unacceptable voltage distortion levels given normal system characteristics and

2) Limit the overall harmonic distortion of the system voltage provided by the utility.

a. Limits to the consumer：

1) Basis for harmonic current limits

The current distortion limits vary for different kinds of power users, and mostly depend on the user's short-circuit ratio (SCR). For a semiconductor converter, SCR is the ratio of the short-circuit capacity of the bus, in MVA, at the point of converter connection to the rating of the converter, in MW. In recognition of this variation, current limits are developed so that the maximum individual frequency harmonic voltage caused by a single customer will not exceed the limits in Table 3.4 for systems that can be characterized by a short-circuit impedance.

Table 3.4 Basis for Harmonic Current Limits

| SCR at PCC | Maximum individual frequency voltage harmonic (%) | Related assumption |
|---|---|---|
| 10 | 2.5-3% | Dedicated system |
| 20 | 2.0-2.5% | 1-2 large customers |
| 50 | 1.0-1.5% | A few relatively large customers |
| 100 | 0.5-1.0% | 5-20 medium size customers |
| 1000 | 0.05-0.10% | Many small customers |

In many cases, the supplying utility must avoid resonances. This can be done by changing the system impedance, adjusting power factor correction capacitor size or location, or designing filters [4].

2) Limits on notches

The average notch depth *d* of the line voltage notch from the sine wave of voltage is shown in Figure 3.1. The notch area $A_N$ of the line voltage notch is the product of the notch depth, in volts, times the width of the notch, measured in microseconds, as shown in (3-8):

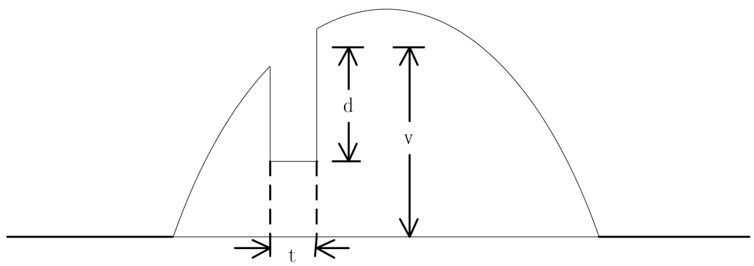


Figure 3.1

$$\text{Notch depth}=\frac{d}{v}\times 100$$

$$A_N = t \cdot d \tag{3-8}$$

The notch limit is applicable in low-voltage systems in which the notch area is easily measured on an oscilloscope. The complete set of limits is given in Table 3.5.

Table 3.5 Notch Limits

| | Special applications | General system | Dedicated system |
|---|---|---|---|
| Notch depth (d) | 10% | 20% | 50% |
| Notch Area ( $A_N$ ) | 16400 $V \cdot \mu s$ | 22800 $V \cdot \mu s$ | 36500 $V \cdot \mu s$ |

Notes: 1. The value $A_N$ for other than 480V systems should be multiplied by V/480.

2. Special applications include hospitals and airports.

3. A dedicated system is exclusively dedicated to a converter load.

3）Current limits

The limits listed in Tables 3.6, 3.7, and 3.8 should be used as system design values for the "worst case" for normal operation (conditions lasting longer than one hour). Variations over time are addressed using percentiles as follows:

1) Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0

times the values given;

2) Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given; and

3) Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given [4].

The percentile concept can be described as follows:

If a set of observations is arranged by ascending value, then the value at the P% position is called the Pth percentile. In the standard, the 99th percentile means the harmonic value is exceeded 1% of the time over the observation period. The values are sampled every 3 seconds in a day or 10 minutes in a week.

In Tables 3.6-3.8, the following definitions apply:

$I_{SC}$ is the maximum short-circuit current at the PCC and

$I_L$ is the maximum load demand current (fundamental frequency component) at the PCC.

Table 3.6 Current Distortion Limits
for Systems Rated 120 V Through 69 kV)

| Maximum Harmonic Current Distortion in percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| Individual Harmonic Order (Odd Harmonics) | | | | | | |
| $I_{SC}/I_L$ | 3≤h<11 | 11≤h≤17 | 17≤h≤23 | 23≤h≤35 | 35≤h | TDD |
| <20 | 4 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| ≥1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |
| Even harmonics are limited to 25% of the odd harmonic limits above | | | | | | |
| Current distortions that result in dc offset are not allowed | | | | | | |
| All power generation equipment is limited to those values of current distortion, regardless of that $I_{SC}/I_L$. | | | | | | |

Table 3.7 Current Distortion Limits
for General Subtransmission Systems
(69 001 V Through 161 000 V)

| Maximum Harmonic Current Distortion in percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| Individual Harmonic Order (Odd Harmonics) | | | | | | |
| $I_{SC} / I_L$ | 3≤h<11 | 11≤h≤17 | 17≤h≤23 | 23≤h≤35 | 35≤h | TDD |
| <20 | 2.0 | 1.0 | 0.75 | 0.3 | 0.15 | 2.5 |
| 20<50 | 3.5 | 1.75 | 1.25 | 0.5 | 0.25 | 4 |
| 50<100 | 5.0 | 2.25 | 2.0 | 0.75 | 0.35 | 6.0 |
| 100<1000 | 6.0 | 2.75 | 2.5 | 1.0 | 0.5 | 7.5 |
| ≥1000 | 7.5 | 3.5 | 3.0 | 1.25 | 0.7 | 10.0 |
| Even harmonics are limited to 25% of the odd harmonic limits above | | | | | | |
| Current distortions that result in dc offset are not allowed | | | | | | |
| All power generation equipment is limited to those values of current distortion, regardless of that $I_{SC} / I_L$. | | | | | | |

Table 3.8 Current Distortion Limits for Systems
Rated ＞161 kV

| Maximum Harmonic Current Distortion in percent of I | | | | | | |
|---|---|---|---|---|---|---|
| Individual Harmonic Order (Odd Harmonics) | | | | | | |
| $I_{sc} / I_L$ | 3≤h<11 | 11≤h≤17 | 17≤h≤23 | 23≤h≤35 | 35≤h | THD |
| <25 | 1 | 0.5 | 0.38 | 0.15 | 0.1 | 1.5 |
| 25<50 | 2 | 1 | 0.75 | 0.3 | 0.15 | 2.5 |
| ≥50 | 3 | 1.5 | 1.15 | 0.45 | 0.22 | 3.75 |
| Even harmonics are limited to 25% of the odd harmonic limits above | | | | | | |
| Current distortions that result in dc offset are not allowed | | | | | | |
| All power generation equipment is limited to those values of current distortion, regardless of that $I_{SC}/ I_L$. | | | | | | |

b. Limits to the utility company:

The distortion limit for utilities limits the maximum voltage distortion at the PPC at which each consumer is connected. At the PCC, system owners or operators should limit line-to-neutral voltage harmonics as follows:

1) Daily 99$^{th}$ percentile very short time (3 s) values should be less than 1.5 times the values given in Table 3.9;

2) Weekly 95$^{th}$ percentile short time (10 min) values should be less than the values given in Table 3.9.

Table 3.9 Voltage Distortion Limits

| Bus Voltage at PCC | Individual Voltage Distortion(%) | Total Voltage Distortion(%) |
|---|---|---|
| $V \leq 1.0$ kV | 5 | 8 |
| 1 kV $< V \leq$ 69 kV | 3 | 5 |
| 69 kV$< V \leq$ 161 kV | 1.5 | 2.5 |
| 161 kV$< V$ | 1 | 1.5 |

c. Limits of Interference With Communication Circuits:

IEEE use the IT product to limit the harmonic interference with communication systems. The IT product is defined as the inductive influence of a current expressed in terms of the product of its root-mean-square magnitude (*I*), in amperes, times its telephone influence factor (TIF). In (3-9), the following definitions apply:

$X$ is the total rms voltage or current;

$X_n$ is the single frequency rms current or voltage at the frequency corresponding to harmonic order n; and

$W_n$ is the single frequency TIF weighting at the frequency corresponding to harmonic order n [3].

$$TIF = \sqrt{\sum \left[ \frac{X_n \cdot W_n}{X} \right]^2} \tag{3-9}$$

The values of $W_n$ are shown in Table 3.10

Table 3.10 Single Frequency Telephone Influence Factor Weighting Values

| FREQ | $W_n$ | FREQ | $W_n$ | FREQ | $W_n$ | FREQ | $W_n$ |
|---|---|---|---|---|---|---|---|
| 60 | 0.5 | 1020 | 5100 | 1860 | 7820 | 3000 | 9670 |
| 180 | 30 | 1080 | 5400 | 1980 | 8330 | 3180 | 8740 |
| 300 | 225 | 1140 | 5630 | 2100 | 8830 | 3300 | 8090 |
| 360 | 400 | 1260 | 6050 | 2160 | 9080 | 3540 | 6730 |
| 420 | 650 | 1380 | 6370 | 2220 | 9330 | 3660 | 6130 |
| 540 | 1320 | 1440 | 6560 | 2340 | 9840 | 3900 | 4400 |
| 660 | 2260 | 1500 | 6680 | 2460 | 10340 | 4020 | 3700 |
| 720 | 2760 | 1620 | 6970 | 2580 | 10600 | 4260 | 2750 |
| 780 | 3360 | 1740 | 7320 | 2820 | 10210 | 4380 | 2190 |
| 900 | 4350 | 1800 | 7570 | 2940 | 9820 | 5000 | 840 |
| 1000 | 5000 | | | | | | |

d. New harmonic source limits:

The harmonics produced by distributed energy resources are limited according to IEEE 1547-2018. This will be discussed in the next chapter.

3. IEC Standards

IEC publishes its harmonic standards in several parts.These publications include related environment and limit standards. The core standards are:

1) IEC 61000-2-2 EMC Part 2-2: Environment-Compatibility Levels for Low Frequency Conducted Disturbances and Signalling in Public Low-Voltage Power Supply Systems.

2) IEC 61000-3-2 EMC Part 3 Limits- Limits for Harmonic Current Emissions (equipment input current ≤ 16 A per phase).

3) IEC 61000-3-12 EMC Part 3 Limits for Harmonic Currents Produced by Equipment Connected to Public Low-Voltage Systems with Input Current >16 A and≤75 A per Phase.

4) IEC 61000-3-6 EMC Part 3 Limits-Assessment of Emission Limits for Connection of Distorting Installations to MV, HV and EHV Power Systems.

IEC 61000-3-2 limits the harmonic current which comes from equipment with input current less than 16A. It classifies equipment into 4 types:

A type: Balanced 3 phase equipment, and all equipment that is not B,C,or D type;

B type: Portable tool and arc welding equipment that is not professional equipment;

C type: Lighting equipment; and

D type: "specific wave" input current equipment, equipment with input power less than 600W, personal computers, television receivers, and refrigerators having one or more variable speed drives;

The harmonic current limits for type A to type D are shown in Table 3.11 to Table 3.13. For Class B equipment, the harmonics of the input current shall not exceed the values given in Table 3.12 multiplied by a factor 1.5 [5].

Table 3.11 Class A Equipment Harmonics Limit

| Odd harmonics | Limit (A) | Even harmonics | Limits (A) |
|---|---|---|---|
| 3 | 2.3 | 2 | 1.08 |
| 5 | 1.14 | 4 | 0.43 |
| 7 | 0.77 | 6 | 0.3 |
| 9 | 0.4 | 8 to 40 | 1.84/h |
| 11 | 0.33 | | |
| 13 | 0.21 | | |
| 15 to 39 | 2.25/h | | |

Table 3.12 Class C  Equipment Harmonics Limit

| Harmonics order | Limit(percentage  %) |
|---|---|
| 2 | 2 |
| 3 | 30×power factor |
| 5 | 10 |
| 7 | 7 |
| 9 | 5 |
| 11 to 39 | 3 |

Table 3.13 Class D Equipment Harmonics Limit

| Harmonic order | Limit (Maximum Current) | |
|---|---|---|
| | Per Watt (mA/W) | (A) |
| 3 | 3.4 | 2.3 |
| 5 | 1.9 | 1.14 |
| 7 | 1 | 0.77 |
| 9 | 0.5 | 0.4 |
| 13 | 0.35 | 0.33 |
| 11 to 39 (odd harmonics only) | 3.85/h | |

When making the emission limits for the equipment between 16A and 75A, IEC 61000-3-12 defines the $R_{sce}$, a characteristic value of a piece of equipment, as follows:

1) $R_{sce} = S_{sc} / (3 \cdot S_{equ})$ for single phase equipment;

2) $R_{sce} = S_{sc} / (2 \cdot S_{equ})$ for interphase equipment; and

3) $R_{sce} = S_{sc} / (S_{equ})$ for three-phase equipment.

In these formulas, $S_{sc}$ is defined as the short circuit power calculated from the nominal phase voltage $U_{nominal}$ and the line impedance *Z* of the system at the PCC as shown in (3-10).

$$S_{sc} = U_{nominal}^2 / Z \tag{3-10}$$

Table 3.14 shows the current emission limits for balanced three-phase equipment. The relative values of even harmonics up to 12 shall not exceed 16/h %. Even harmonics above the 12th are taken into account in the total harmonic current (THC) and the partial weighted harmonic current (PWHC) in the same way as odd order harmonics.

Table 3.14 Harmonic Current Limits for
Balanced Three-Phase Equipment Between 16A and 75A

| Minimum $R_{sce}$ | Admissible individual harmonic current $I_h / I_{ref}$ % | | | | Admissible harmonic parameters % | |
|---|---|---|---|---|---|---|
| | $I_5$ | $I_7$ | $I_{11}$ | $I_{13}$ | $THC / I_{ref}$ | $PWHC / I_{ref}$ |
| 33 | 10.7 | 7.2 | 3.1 | 2 | 13 | 22 |
| 66 | 14 | 9 | 5 | 3 | 16 | 25 |
| 120 | 19 | 12 | 7 | 4 | 22 | 28 |
| 250 | 31 | 20 | 12 | 7 | 37 | 38 |
| ≥350 | 40 | 25 | 15 | 10 | 48 | 46 |

In Table 3.14,

$I_{ref}$ is the reference current, the input of which shall be measured using the average method defined in 61000-3-12 and

$I_h$ is the harmonic order component.

THC is the total RMS value of harmonic components of order 2 to 40, shown in (3-11).

PWHC is a selected group of higher order harmonic currents (In the IEC standard from order 14 to order 40), weighted with the harmonic order h, as shown in (3-12).

$$THC = \sqrt{\sum_{h=2}^{40} I_h^2} \quad (3\text{-}11)$$

$$PWHC = \sqrt{\sum_{h=14}^{40} h \cdot I_h^2} \quad (3\text{-}12)$$

IEC 61000-3-6 specifies the harmonic emission limit values of installations in medium, high, and extra high voltage conditions. The range of medium and high voltage is 1 to 35kV and 35 to 230kV. The technical report considers that the harmonic current should be specified by the voltage distortion so that the total distortion caused by all installations will not exceed the allowable total voltage distortion level.

The compatibility levels for harmonic voltages in LV and MV systems are from IEC 61000-2-2 [5] and IEC 61000-2-12 [6]. These compatibility levels shall be understood to relate to quasi-stationary or steady-state harmonics, and are given as reference values for both long-term effects and very-short-term effects. The long-term effects relate mainly to thermal effects on cables, transformers, motors, capacitors, etc. They arise from harmonic levels that are sustained for 10 minutes or more.Very short-term effects relate mainly to disturbing effects on electronic devices that may be susceptible to harmonic levels sustained for 3 seconds or less. Transients are not included.

With reference to long-term effects, the compatibility levels for individual harmonic components of the voltage are given in Table 3.15. The compatibility level for the total harmonic distortion is *THD* = 8 %. With reference to the very-short term effects, the compatibility levels for individual harmonic components of the voltage are the values given in Table 3.15 multiplied by a factor $k_{hvs}$, where $k_{hvs}$ is calculated as shown in (3-13). The compatibility level for the total harmonic distortion for very short-term effects is THD =11%.

$$k_{hvs} = 1.3 + \frac{0.7}{45} \cdot (h - 5) \tag{3-13}$$

IEC uses two sets of reference levels for the purpose of overall EMC coordination. One is the compatibility level (shown in table 3.15), and the other is the planning level (shown in Table 3.16). The compatibility level is used to coordinate the emission and immunity of equipment which is part of, or supplied by, a supply system in order to ensure EMC in the whole system. The planning level is used to determine emission limits for all distorting installations. Planning levels are specified by the system operator or owner for all system voltage levels, and may be made available to individual customers on request. Planning levels for harmonics are equal to or lower than compatibility levels and they should allow coordination of harmonic voltages between different voltage levels. The numbers in Table 3.16 are indicative values because planning levels will be different in a variety of different cases.

Table 3.15 Compatibility Levels for Individual Harmonic Voltages

in Low and Medium Voltage Networks

| Odd harmonics non-mutiple of 3 | | Odd harmonics mutiple of 3 | | Even harmonics | |
|---|---|---|---|---|---|
| Harmonic order h | Harmonic voltage % | Harmonic order h | Harmonic voltage % | Harmonic order h | Harmonic voltage % |
| 5 | 6 | 3 | 5 | 2 | 2 |
| 7 | 5 | 9 | 1.5 | 4 | 1 |
| 11 | 3.5 | 15 | 0.4 | 6 | 0.5 |
| 13 | 3 | 21 | 0.3 | 8 | 0.5 |
| 17≤h≤49 | $2.27 \cdot \frac{17}{h} - 0.27$ | 21≤h≤45 | 0.2 | 10≤h≤50 | $0.25 \cdot (\frac{10}{h} + 1)$ |

NOTE: The compatibility level for the total harmonic distortion is THD = 8% [6].

Table 3.16 Indicative Planning Levels for

Harmonics in MV, HV and EHV Power Systems

| Odd harmonics non-mutiple of 3 | | | Odd harmonics mutiple of 3 | | | Even harmonics | | |
|---|---|---|---|---|---|---|---|---|
| Harmonic order h | Harmonic voltage % | | Harmonic order h | Harmonic voltage % | | Harmonic order h | Harmonic voltage % | |
| | MV | HV-EHV | | MV | HV-EHV | | MV | HV-EHV |
| 5 | 5 | 2 | 3 | 4 | 2 | 2 | 1.8 | 1.4 |
| 7 | 4 | 2 | 9 | 1.2 | 1 | 4 | 1 | 0.8 |
| 11 | 3 | 1.5 | 15 | 0.3 | 0.3 | 6 | 0.5 | 0.4 |
| 13 | 2.5 | 1.5 | 21 | 0.2 | 0.2 | 8 | 0.5 | 0.4 |
| 17≤h≤49 | $1.9 \cdot \frac{17}{h} - 0.2$ | $1.2 \cdot \frac{17}{h}$ | 21≤h≤45 | 0.2 | 0.2 | 10≤h≤50 | $0.25 \cdot \frac{10}{h} + 0.22$ | $0.19 \cdot \frac{10}{h} + 0.16$ |

The indicative planning levels for the total harmonic distortion are: $THD_{MV}$ = 6.5% and $THD_{HV-EHV}$ = 3%. With reference to very short term effects of harmonics (3 second or less), planning levels for individual harmonics should be multiplied by the factor $k_{hvs}$ as given by (3-8).

To establish limits for installations, an application of the general summation law is necessary to determine the global contribution of all harmonic sources present in a particular MV HV or EHV system. (Only MV systems are considered in this work.) Indeed, for each harmonic order, the actual harmonic voltage in a MV system results from the vector summation of the harmonic voltage coming from the upstream system (note that the upstream system may be an HV or another MV system for which intermediate planning levels have been already set) and of the harmonic voltage resulting from all distorting installations connected to the considered MV and LV system. This total harmonic voltage should not exceed the planning level of the MV system, as shown in (3-14):

$$L_{hMV} = \sqrt[\alpha]{G_{hMV+LV}^{\alpha} + (T_{hUM} \cdot L_{hUS})^{\alpha}} \tag{3-14}$$

The global harmonic voltage contribution that can be allocated to the total of MV and LV installations supplied from the considered MV system is given by (3-15)

$$G_{hMV+LV} = \sqrt[\alpha]{L_{hMV}^{\alpha} - (T_{hUM} \cdot L_{hUS})^{\alpha}} \tag{3-15}$$

In (3-9) and (3-10) the following definitions apply:

$G_{hMV+LV}$ is the maximum overall level of the $h^{th}$ harmonic that can be present at this medium voltage bus;

$L_{hMV}$ is the planning level of the $h^{th}$ harmonic in the MV system;

$L_{hUS}$ is the planning level of the $h^{th}$ harmonic of the upstream system;

$T_{hUM}$ is the transfer coefficient which represents the influence of the harmonic level of the upstream system on the medium voltage system and is usually about 1; and

α is the summation law exponent with values given in Table 3.17.

Table 3.17. Summation Exponent

| Harmonic order | α |
|---|---|
| h<5 | 1 |
| 5≤h≤10 | 1.4 |
| h>10 | 2 |

The emission limits for individual installations connected to the bus are allocated as shown in (3-16):

$$E_{Uhi} = G_{HV+LV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \tag{3-16}$$

In (3-16), the following definitions apply:

$E_{Uhi}$ is the allowed harmonic voltage emission limit of order h for the installation (i) directly supplied at MV;

$S_i$ is the power of the installation; and

$S_t$ is the total power supply capacity of the busbar [7].

4. An Example

A small case is given to illustrate the application of the Chinese, IEEE, and IEC standards. As shown in Figure 3.2, the power supply voltage is 12.47 kV and three users are supplied at the PCC point A via the system impedance. The power load demand of the three users is 1.5 MVA, 1.5 MVA and 4 MVA. The short circuit current at bus A is 4200 A. The purpose of this example is to determine the harmonic current limits for the $2^{nd}$, $3^{rd}$, $8^{th}$, $15^{th}$, and $25^{th}$ harmonics for the

4 MVA load using each of the standards. Line resistance and capacitance are neglected for simplicity.

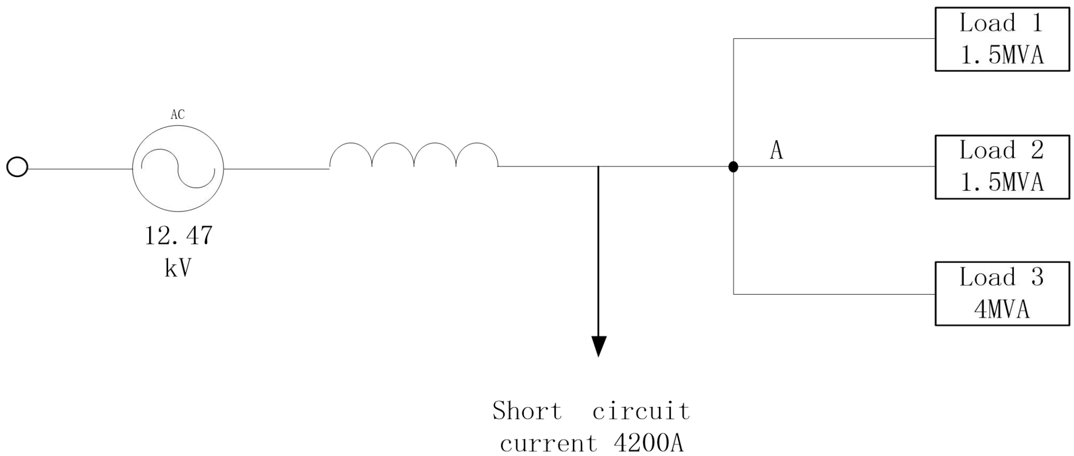


Figure 3.2 Example

A. Using the Chinese Standard.

The Chinese nominal voltage is 10kV instead of 12.47kV. So, we can assume that the system is running at 10kV. The line impedance can be found as shown in (3-17).

$$Z_{line} = \frac{12.47 \times 10^3}{\sqrt{3} \times 4200} = j1.714\Omega \tag{3-17}$$

So, at the 10kV voltage level, the short circuit current can be determined as shown in (3-18).

$$I_{short} = \frac{10 \times 10^3}{\sqrt{3} \times 1.714} = 3368.4A \tag{3-18}$$

The short circuit power is shown in (3-19).

$$S_i = \sqrt{3} \times 3.368 \times 10^3 \times 10 \times 10^3 = 58.33MVA \tag{3-19}$$

This short circuit power is different from the reference capacity in Table 3.3, so we can use equation 3.7 to modify the current as shown in (3-20).

$$I_h = \frac{58.33}{100} \cdot I_{hp} \tag{3-20}$$

The numbers in Table 3.3 can be used to get the limit for each harmonic and then these can be allocated to load 3 by using (3-6) and Table 3.2.

$$I_{h2}=\frac{58.33}{100}\times 26\times (\frac{4}{7})^{\frac{1}{2}}=11.64A$$

$$I_{h3}=\frac{58.33}{100}\times 20\times (\frac{4}{7})^{\frac{1}{1.1}}=7.01A$$

$$I_{h8}=\frac{58.33}{100}\times 8.5\times (\frac{4}{7})^{\frac{1}{2}}=3.75A$$

$$I_{h15}=\frac{58.33}{100}\times 4.1\times (\frac{4}{7})^{\frac{1}{2}}=1.81A$$

$$I_{h25}=\frac{58.33}{100}\times 4.1\times (\frac{4}{7})^{\frac{1}{2}}=1.81A$$

B. Using the IEEE Standard

First, we can get the load current as shown in (3-21).

$$I_L=\frac{4\times 10^6}{12.47\times 10^3\times\sqrt{3}}=0.185kA=185.19A \qquad (3\text{-}21)$$

Then, to use Table 3.7, we need to calculate the ratio between the load current and the short circuit current, which is shown in (3-22).

$$I_{SC}/I_L=\frac{4.2}{0.185}=22.7 \qquad (3\text{-}22)$$

With this ratio, we can calculate each harmonic limit using the numbers in Table 3.7.

$$I_{h2}=25\%\times 3.5\%\times 185.19=1.618A$$

$$I_{h3}=3.5\%\times 185.19=6.48A$$

$$I_{h8}=25\%\times 3.5\%\times 185.19=1.62A$$

$$I_{h15}=1.75\%\times 185.19=3.24A$$

$$I_{h25} = 0.5\% \times 185.19 = 0.926A$$

C. Using the IEC Standard

We can get voltage harmonic limits for HV and MV starting from the planning levels in Table 3.16.

$$L_{2MV} = 1.8\%,\ L_{3MV} = 4\%,\ L_{8MV} = 0.5\%,\ L_{15MV} = 0.3\%,\ L_{25MV} = 1.9 \cdot \frac{17}{25} - 0.2 = 0.136\%$$

$$L_{2US} = 1.4\%,\ L_{3US} = 2\%,\ L_{8US} = 0.4\%,\ L_{15US} = 0.3\%,\ L_{25US} = 1.2 \times \frac{17}{25} = 1.092\%$$

From the planning levels, global allowable harmonic voltage levels can be determined at bus A according to (3-15) and using the summation exponents in Table 3.17.

$$G_{2MV} = \sqrt[1]{1.8^1 - 1 \times 1.4^1} = 0.4\%$$

$$G_{3MV} = \sqrt[1]{4^1 - 1 \times 2^1} = 2\%$$

$$G_{8MV} = \sqrt[1.4]{0.5^{1.4} - 0.4^{1.4}} = 0.195\%$$

$$G_{15MV} = \sqrt[2]{0.3^2 - (\frac{2}{3}) \times 0.3^2} = 0.173\%$$

$$G_{25MV} = \sqrt[2]{1.092^2 - 1 \times 0.136^2} = 0.726\%$$

Note that if $\alpha$ =1 is used to calculate the $15^{th}$ harmonic limit, we would get 0% which is unrealistic. So, we use $\alpha = \frac{2}{3}$ instead. The allocation equation (3-13) is used to determine the limit for load 3.

$$E_{Uh2} = 0.4 \times \frac{4}{7} = 0.23\%$$

$$E_{Uh3} = 2 \times \frac{4}{7} = 1.14\%$$

$$E_{Uh8} = 0.195 \times \sqrt[1.4]{\frac{4}{7}} = 0.13\%$$

$$E_{Uh15} = 0.173 \times \sqrt[2]{\frac{4}{7}} = 0.131\%$$

$$E_{Uh25} = 0.726 \times \sqrt[2]{\frac{4}{7}} = 0.549\%$$

The voltage limits can be converted into current limits using the line impedance.

$$I_{h2} = \frac{0.23}{100 \times 2 \times 1.714} \times \frac{12.47 \times 10^3}{\sqrt{3}} = 4.8A$$

$$I_{h3} = \frac{1.14}{100 \times 3 \times 1.714} \times \frac{12.47 \times 10^3}{\sqrt{3}} = 15.96A$$

$$I_{h8} = \frac{0.13}{100 \times 8 \times 1.714} \times \frac{12.47 \times 10^3}{\sqrt{3}} = 0.68A$$

$$I_{h15} = \frac{0.131}{100 \times 15 \times 1.714} \times \frac{12.47 \times 10^3}{\sqrt{3}} = 0.367A$$

$$I_{h25} = \frac{0.549}{100 \times 25 \times 1.714} \times \frac{12.47 \times 10^3}{\sqrt{3}} = 0.922A$$

The summary of the results is shown in Table 3.18.

Table 3.18 Comparison of Results

| Harmonic Order | | 2 | 3 | 8 | 15 | 25 |
|---|---|---|---|---|---|---|
| Current limit on load 3 (A) | Chinese Standard | 11.64 | 7.01 | 3.75 | 1.81 | 1.81 |
| | IEEE Standard | 1.618 | 6.48 | 1.62 | 3.24 | 0.926 |
| | IEC Standard | 4.8 | 15.96 | 0.68 | 0.367 | 0.922 |

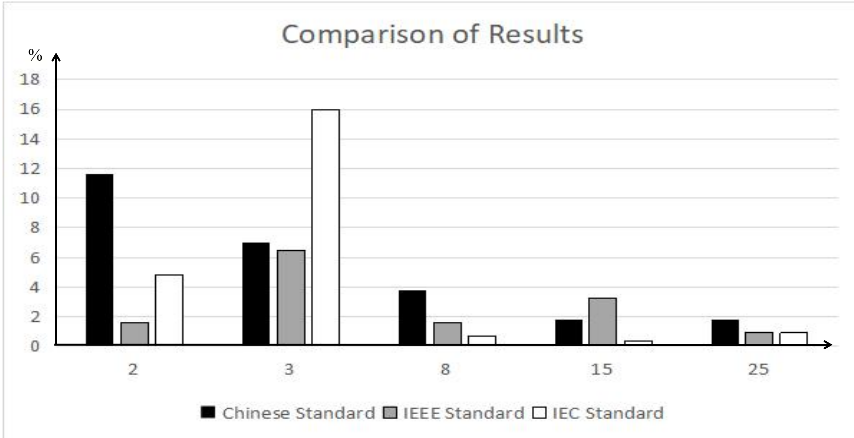


Figure 3.3 Comparison of Results

From the table we can conclude that the IEEE standard is very conservative and strict for even harmonics. The IEC standard has a looser requirement for harmonics in the middle section, but as the order of harmonic increases, the attenuation is fast, which is caused by the increase in impedance of the system. The Chinese standard has a tendency to linearly decrease with harmonic order, but it is very loose in the requirements for even orders, especially the second harmonic.

## Ⅲ Unbalanced Three Phase Standard

### 1. Chinese Standard.

#### a. Terms

*Voltage unbalance (imbalance)*: Voltage unbalance occurs when the magnitude of the three phase voltages are not all the same or the angles of the three phase voltages are not 120° apart, or these two conditions happen together.

*Unbalance factor*: The unbalance level of the power system is represented by the ratio of the fundamental frequency term of the negative-sequence component or the zero-sequence component to the positive-sequence component (RMS value).Parameters $\varepsilon_{U2}, \varepsilon_{U0}$ and $\varepsilon_{I2}, \varepsilon_{I0}$ are used to represent the negative-sequence unbalance factor and zero-sequence unbalance factor for the voltage and current. The equations are shown in (3-20) for voltage.

$$\varepsilon_{U2} = \frac{U_2}{U_1} \times 100(\%)$$
$$\varepsilon_{U0} = \frac{U_0}{U_1} \times 100(\%) \tag{3-20}$$

In (3-20), $U_0, U_1$ and $U_2$ are the RMS voltage values of the zero-sequence component, positive-sequence component, and negative-sequence component. The current parameter expression is the same as the voltage in (3-20) with *I* replacing *U*. For those systems which don't have a zero-sequence component, the unbalance factor can also be calculated as shown in (3-21).

$$\varepsilon_2 = \sqrt{\frac{1-\sqrt{3-6L}}{1+\sqrt{3-6L}}} \times 100\% \tag{3-21}$$

In (3-22), *L* is defined as shown in (3-22) where a, b, and c are the magnitudes of the three phase voltages or currents.

$$L = \frac{(a^4+b^4+c^4)}{(a^2+b^2+c^2)^2} \tag{3-22}$$

**b. Chinese Standard**

The recommendations in the Chinese standards are as follows:

1) The unbalance factor (negative sequence factor) of the PCC voltage should not exceed 2% under normal conditions and 4% under temporary (3s-1min) conditions and

2) The voltage negative-sequence factor caused by each user connected to the PCC should not exceed 1.3% under normal conditions and 2.6% under temporary (3s-1min) conditions [8].

**2. IEC standards**

The compatibility level for voltage unbalance in LV and MV systems is shown in Table 3.19 from references IEC 61000-2-2 and IEC 61000-2-12. A level of 3% may occur typically on LV networks and MV networks which supply smaller installations connected as single-phase loads (or between phases) [9].

Table 3.19 Compatibility Level for Voltage Unbalance in Low and Medium Voltage Systems

| Voltage unbalance factor (negative sequence) |
|---|
| 2% |

These are voltage unbalance levels that can be used for the purpose of determining emission limits, taking into consideration all unbalanced installations. Planning levels are specified by the system operator or owner for all system voltage levels and can be considered as internal quality objectives of the system operator or owner, and may be made available to individual customers on request. Planning levels for voltage unbalance are equal to or lower than compatibility levels and they should allow coordination of voltage unbalances between different voltage levels. Only indicative values may be given because planning levels will differ from case to case, depending on system structure and circumstances. Indicative values of planning levels for voltage unbalance are shown in Table 3.20.

Table 3.20: Indicative Values of Planning Levels for Voltage Unbalance (Negative-Sequence Component) in MV, HV and EHV Power Systems

| Voltage level | Planning level (%) |
|---|---|
| MV | 1.8 |
| HV | 1.4 |
| EHV | 0.8 |

**3. Standard used in America**

There is not a uniform unbalanced three phase standard in North America. The requirements are established by each company. Typical allowable levels of voltage unbalance are 2-5%.

## Ⅳ Flicker standard

The flicker definition, measuring method, and recommendations are almost same between IEEE, IEC, and Chinese industry.

**1. Definition:**

For flicker, the following terms and definitions are frequently used in the standards:

$T_{short}$ is short term interval for the $P_{st}$ evaluation (NOTE: Unless otherwise specified, the short term interval $T_{short}$ is 10 min.);

$P_{st}$ is short-term flicker severity;

$T_{long}$ is long term time interval for the $P_{lt}$ evaluation,which is always an integer multiple of the short term flicker severity evaluation $P_{st}$. (NOTE: Unless otherwise specified,the long term interval $T_{long}$ is12×10 min, i.e.2 hours);

$P_{lt}$ is long-term flicker severity;

$P_{inst}$ is instantaneous flicker sensation;

$D_{hp}$ is relative half period rms value of the voltage;

$d_c$ is maximum steady state voltage change during an observation period; and

$d_{\max}$ is maximum absolute voltage change during the observation period.

**2. Differences Between Chinese and IEEE Standards**

**(1) Correction Factor**

Due to the differences in magnitude and frequency between U.S. (120V 60Hz) and China (220V 50 Hz), there is a correction factor applied to the measured values of $P_{st}$ and $P_{lt}$. The flickermeter is set to operate under the dedicated voltage and frequency condition shown in the reference table in Table 3.21. The resultant flicker readings are generally within some deviation if the measuring parameter has been adjusted to the voltage/ frequency combination in the first column. The deviations are generally well within the ±5% tolerance specification that is used throughout this standard, and it is impractical to devise test specifications for the multiple combinations as these would increase instrument certification cost without providing substantial benefits. These factors are generally conservative [10].

Table 3.21 Correction Factor for Other Voltage /Frequency Combinations

| Voltage and Frequency | Correction Factor | Reference table |
|---|---|---|
| 220V 50Hz | 0.97 | 230V 50Hz |
| 220V 60Hz | 0.97 | 230V 60Hz |
| 100V 50Hz | 0.9 | 120V 50Hz |
| 100V 60Hz | 0.9 | 120V 60Hz |

**(2) Chinese flicker standard**

The Chinese standard recommends that all the $P_{lt}$ values at any PCC should not exceed the limits in Table 3.22. There is no limit for $P_{st}$ in the Chinese standard [11].

Table 3.22 Chinese Flicker Standard

| $P_{lt}$ | |
|---|---|
| ≤110kV | ＞110kV |
| 1 | 0.8 |

**(3) IEEE and IEC levels**

The limit part of IEEE Std 1453-2011 adopts the IEC 61000-3-7 standard. It also gives the values for LV compatibility levels and planning levels for MV, HV, EHV levels shown in Table 3.23 and 3.24. A small difference that IEEE combines the $P_{st}$ and $P_{lt}$ values for a full week and calculates summary statistics for the week. It requires that 95% probability values should not exceed the planning level and allows that 99% probability values may exceed the planning level by a factor (1−1.5) depending on system conditions to be determined by the system operator [12].

Table 3.23 Compatibility Levels for Flicker in Low Voltage Systems

| Parameters | Compatibility levels |
|---|---|
| $P_{st} / P_{st95\%}$ | 1 |
| $P_{lt} / P_{st95\%}$ | 0.8 |

Table 3.24 Indicative Values of Planning Levels for Flicker in MV, HV and EHV Power Systems

| Parameters | Planning levels | |
|---|---|---|
| | MV | HV-EHV |
| $P_{st}$ | 0.9 | 0.8 |
| $P_{lt}$ | 0.7 | 0.6 |

Chinese, IEEE, and IEC standards are the same in allocating flicker limits to all installations connected to the PCC, which is specified in IEC 61000-3-7. The flicker allocation method is very muck like the harmonic method, as shown in (3-23) and (3-24).

$$E_{Psti} = G_{PstMV} \cdot \alpha \sqrt{\frac{S_i}{(S_t - S_{LV})}} \tag{3-23}$$

$$E_{Plti} = G_{PltMV} \cdot \alpha \sqrt{\frac{S_i}{(S_t - S_{LV})}} \tag{3-24}$$

In (3-23) and (3-24), the following definitions apply:

$E_{Psti}$, $E_{Plti}$ are the limits for the installation directly connected at MV;

$G_{PstMV}$, $G_{PltMV}$ are the planning levels at MV level, if the flicker sources at other levels are neglected;

$S_t$ is the total supply capacity at the given bus; and

$S_{LV}$ is the the power capacity at the lower voltage level.

$\alpha = 3$ is mostly used in (3-23) and (3-24).

**(4) The Voltage Fluctuation Limitation**

The voltage fluctuation limitations of Chinese and IEEE standards are different.The first table gives the regular or periodic voltage fluctuation limits in China. The flicker problem is in some ways evaluated and limited by voltage deviation [13].

The IEEE standard  doesn't evaluate the flicker issue using a voltage deviation method. The only similar part is they give an allowable step (rapid) voltage change limit. Step (rapid) voltage changes are often caused by motor starting and switching operations of equipment such as capacitors.

Table 3.25 Chinese Voltage Deviation Limits

| r/(times/h) | d (%) | |
|---|---|---|
| | LV,MV | HV |
| r≤1 | 4 | 3 |
| 1＜r≤10 | 3* | 2.5* |
| 10＜r≤100 | 2 | 1.5 |
| 100＜r≤1000 | 1.25 | 1 |

Notes:

1. For very infrequent changes, less than 1 time a day for example,the fluctuation value d can exceed the limit.
2. For those aperiodic fluctuations caused by some load like arc furnaces, the limitation is shown with *.
3. The voltage levels are:

LV: $U_N$＜1kV

MV:1kV＜$U_N$≤35kV

HV:35kV＜$U_N$

IEEE 1547-2018 requires that when the PCC is at medium voltage, the considered distributed energy resources (DER) shall not cause step or ramp changes in the RMS voltage at the PCC exceeding 3% of nominal voltage or exceeding 3% per second averaged over a period of one second. When the PCC is at low voltage, the DER shall not cause step or ramp changes in the RMS voltage exceeding 5% of nominal and exceeding 5% per second averaged over a period of one second.

IEC 61000-3-7 also gives recommended limits for step voltage changes as shown in Table 3.26 [14].

Table 3.26 Indicative Planning Levels for Step Voltage Changes as a Function of the Number of Such Changes in a Given Period

| Number of Changes n | $\Delta V / V_n$ % | |
|---|---|---|
| | MV | HV/EHV |
| n≤4 per day | 5-6 | 3-5 |
| n≤2 per hour and ＞4 per day | 4 | 3 |
| 2<n≤10 per hour | 3 | 2.5 |

# CHAPTER 4. POWER QUALITY STANDARDS COMPARISON FOR DISTRIBUTED ENERGY RESOURCES

## Ⅰ Introduction of Distributed Resources

Compared to a typical power plant, distributed energy resources (DER) use small size generators whose capacity is usually less than 10MVA. Distributed energy resources can create power quality issues when connecting to the power grid. The first reason is that different kind of sources can cause different power quality issues. The second reason is that parameter of each DER equipment can vary a lot at different places. When multiple DER are connected together, power quality problems can arise.

Due to environmental reasons, economic reasons, or political reasons, DER has made a lot of progress over the years. Great changes have taken place in wind, solar, and even geothermal power generation. Some people believe that the whole power system will be changed into something new and high-tech where DER can be distributed everywhere in the system like the load. The interconnected power grid can also be smaller. But whether this prediction could come true is still under debate. The challenge is from two aspects: one is whether the new system can make a profit as it did in the past, and the other is whether some technical problems can be solved in a short period of time in the near future. However, no matter what problems still remain, DER all over the world are trying to play a more and more important role in the power supply market. The power quality problem is becoming an important issue to be addressed.

## Ⅱ Power quality issues with distributed resources.

Usually, the DER can be treated as an inverter connected to the electric power system (EPS). Under normal conditions, these DER are monitored by the utility company to make sure the power quality produced by the inverter meets applicable requirements. But things change when a fault or abnormal condition occurs around the DER.

More comprehensive knowledge about the harmonic current characteristic of medium-sized and large-sized photovotaic (PV) inverters is needed, particularly in order to improve the accuracy of respective harmonic studies. Harmonic models for PV inverters require a lot of information from the manufactures and it is usually kept confidential. Due to this lack of knowledge, suitable manufacturer-specific harmonic models that can to be used for studies of harmonic emission, harmonic instabilities or harmonic resonance are still missing. This includes also aggregated harmonic models, e.g. for representing a PV plant consisting of multiple PV inverters. Measurement-based models seem to be a possible approach to improve the model accuracy compared to the simple models based on constant current sources. However, the combination of the different driving factors, like supply voltage distortion, network impedance, magnitude of supply voltage and output power of the PV-inverter, is still not well known or validated. Comprehensive knowledge about the possible impact of PV inverters combined with the harmonic network impedance, particularly their contribution to harmonic resonances in public LV grids, is still missing. General and final conclusions about the impact of PV power on the harmonic levels are not known and might not even be possible. It strongly depends on the situation including the size of the PV installation, the harmonic impedance at the connection point and the PV inverter models used. However, a significant increase of harmonic levels on a large scale has not been observed yet.

Also,wind conditions have a direct impact on the voltage fluctuations and flicker caused by wind turbines. Wind speed changes, tower shadow effects, wind shear, yaw error and other factors can cause fluctuations in the output power of wind turbines, especially average wind speed and turbulence intensity. Because the increase of the wind turbine power is proportional to the cube of the wind speed, the power fluctuation caused by the wind speed fluctuation is also relatively large in the region above the rated wind speed.

The power fluctuation frequency caused by the tower shadow effect, the wind shear bias, and the navigation error are related to the speed of the wind turbine. For a modern three-blade wind turbine, its power fluctuation frequency is three times that of the wind turbine blade rotation.  After the wind turbine is connected to the grid, it also can produce large voltage fluctuations and flicker. The important parameters related to the strength of the grid are the impedance of the power supply at the common connection point, the impedance and X/R ratio of the line interconnecting to the grid and the ratio of the capacity of the conventional power generation system to the capacity of the wind turbine. The larger the capacity of the node or the short circuit current at the common connection point, the smaller the voltage fluctuation and flicker caused by the wind turbine. Appropriate controls of wind power can effectively cause the voltage fluctuation caused by the active power to be compensated by the voltage fluctuation caused by the reactive power, thereby reducing the total average flicker value.

In addition, for three-phase new energy sources, there is a possibility of  asymmetrical faults occurring, such as line to ground, line to line or line to line to ground short-circuits. Under normal operating conditions, due to the unbalanced three-phase power of the new energy source, or the asymmetry of the structure and parameters of the three-phase grid-connected converter, or the error in detection and control, there could be a certain degree of imbalance in the output power. Moreover, with the popularization of small distributed new energy power generation technologies such as small wind turbines and PV panels, the number of single-phase distributed power sources may increase. The connection of these single-phase distributed power sources will cause three-phase unbalance in the power grid to a certain extent, or make the existing three-phase unbalance of the power grid more serious.

When the system is in a three-phase unbalanced operation state, due to the existence of the negative sequence component, it would do harm to the connected electrical equipment. A big negative sequence current component in the three-phase unbalanced system may cause tripping or some malfunction of automatic devices, which threatens the safe operation of the power grid. The negative sequence voltage can produce breaking torque in induction motors, which causes the maximum torque and output power of the induction motor to drop. It may also cause mechanical vibrations of the motor. Moreover, three-phase voltage imbalance can make an inverter's triggering angle asymmetrical, and the inverter will generate large non-characteristic harmonics.

## Ⅲ The standard differences and comparison.

### 1. Chinese Standard

The power quality requirements of the Chinese standard and the IEC standard for distributed power sources are substantially equivalent to their corresponding standards for utility grids. For the measurement of power quality parameters, Chinese standards are also implemented in accordance with the corresponding IEC standards. The specific harmonic, flicker and three-phase imbalance criteria are listed in Chapter 3.

The difference is that China has made additional regulations on the harmonic requirements of its photovoltaic power generation projects and specifies the output distortion requirements for the photovoltaic systems. See Table 4.1 for details [15].

Table 4.1 Harmonic Requirements for Photovoltaic Systems in China

| Odd harmonics | | Even harmonics | |
|---|---|---|---|
| Harmonic order h | Current limit % | Harmonic order h | Current limit % |
| 3≤h≤9 | 4 | 2≤h≤8 | 1 |
| 11≤h≤15 | 2 | | |
| 17≤h≤21 | 1.5 | 10≤h≤32 | 0.5 |
| 23≤h≤33 | 0.6 | | |

Notes:

1. The unit of current limit is the ratio of the $h^{th}$ harmonic current to the output current of the inverter.

2.The total harmonic current distortion should be less than 5% of the inverter's rated output current to insure no adverse effects on other equipment connected to the grid.

3.The even harmonic limit should be less than 25% of the odd harmonic limit.

**2. The standards used in U.S.A.**

There are currently two major interconnection standards for DER in the United States. These are IEEE Std 929-2000 and IEEE Std 1547-2018. The IEEE Std 929-2000 was designed for the requirements of photovoltaic system inverters that are connected to the grid system. This standard has been withdrawn and essentially replaced by IEEE 1547-2018. The IEEE Std 1547-2018 standard has now evolved into a national standard in the United States, and all types of DER must meet this standard. The standard is actively being revised and improved. At present, these two standards tend to be unified in many aspects.

**(1) Flicker standard**

The flicker value created by the DER at the PCC point shall not exceed the limits listed in Table 4.2. Any exception to the limits shall be approved by the Area electric power system (EPS) operator with consideration of other sources of flicker within the area EPS [16].

Table 4.2 Minimum Individual DER Flicker Emission Limits

| $E_{Pst}$ | $E_{Plt}$ |
|---|---|
| 0.35 | 0.25 |

Limit allocation and measurement methods for flicker are further addressed in IEEE Std 1453 and IEC/TR 61000-3-7.

**(2) Harmonic Limits**

The harmonics, interharmonics, and total rated-current distortion (TRD) at the point of applicability (RPA) shall not exceed the limits specified in IEEE 1547-2018 and listed in Tables 4.3 and 4.4. The methodology for measuring harmonic and inter-harmonic values in this requirement is defined in IEEE Std 519-2014. Note that Table 4.3 and Table 4.4 differ from any table in IEEE Std 519. In the IEEE 1547-2018 standard, the new term “total rated-current distortion” (TRD) was introduced and used instead of total demand distortion (TDD) (in Table 4.3) and the even order current distortion limits above the second order are relaxed for DER (in Table 4.4).

Table 4.3 Maximum Odd Harmonic Current Distortion in Percent of Rated Current

| Odd harmonic limits(%) | h＜11 | 11≤h＜17 | 17≤h＜13 | 23≤h＜35 | 35≤h | Total rated current distortion (TRD) |
|---|---|---|---|---|---|---|
| Limit % | 4 | 2 | 1.5 | 0.6 | 0.3 | 5 |

Table 4.4 Maximum Even Harmonic Current Distortion in Percent of Rated Current

| Even harmonic limits(%) | h=2 | h=4 | h=6 | 8≤h＜50 |
|---|---|---|---|---|
| Limit % | 1 | 2 | 3 | Associated range specified in Table 4.3 |

The total rated current distortion can be calculated using (4-1).

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} \times 100\% \tag{4-1}$$

In (4-1),

$I_1$ is the fundamental current as measured at the RPA;

$I_{rated}$ is the DER rated current capacity (transformed to the RPA when a transformer exists) between the DER unit and the RPA; and

$I_{rms}$ is the root-mean-square of the DER current, inclusive of all frequency components, as measured at the RPA.

**(3) Limit of over voltage contribution**

The DER shall not cause the instantaneous voltage on any portion of the area EPS to exceed the magnitude and cumulative durations shown in Figure 4.1. The cumulative duration shall only include the sum of durations for which the instantaneous voltage exceeds the respective threshold over a one-minute time window [17].

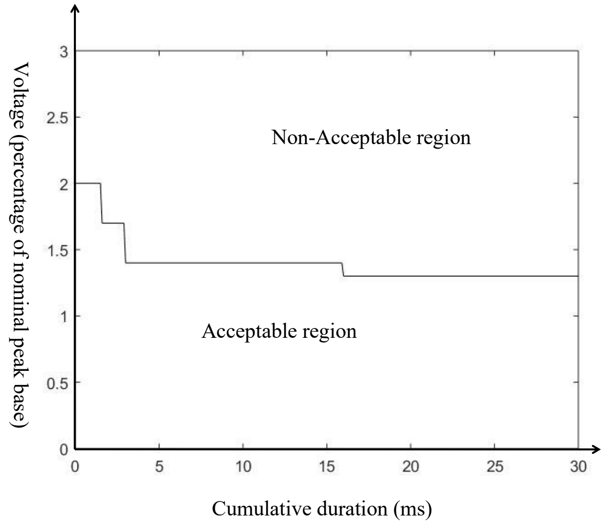

Figure 4.1 Transient voltage limits

3. The IEC Standard

IEC manages DER through proposed new or revised Technical Reports. They are

1) IEC 61000-3-16 (harmonics produced by DER equipment, less than 75 A);

2) IEC 61000-3-17 (flicker produced by DER equipment, less than 75 A); and

3) IEC 61000-3-6 (harmonics), -3-7 (flicker), and -3-13 (unbalance) for installations, generally above 50 kVA。

Modifications in future editions will consider energy producing installations.For single phase and three-phase DER, the tentative flicker limit is $P_{st} < 0.45$ . These reports also give harmonic limits as shown in Table 4.5. In Table 4.5, the following definitions apply：

$\lambda$ is the power factor of the equipment;

$I_{rms}$ is the maximum output current; and

$I_h$ is the harmonic current component.

Table 4.5 IEC Harmonic Limits for Single and Three Phase DER

| $S$ | Admissible individual harmonic current $I_h / I_{rms}$ % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $I_3$ | $I_5$ | $I_7$ | $I_9$ | $I_{11}$ | $I_{13}$ | ODD harmonics $I_{15}$ to $I_{39}$ | EVEN harmonics $I_2$ to $I_{40}$ |
| ≤600 VA | $30 \cdot \lambda$ | 10 | 7 | 5 | 3 | 3 | 3 | 2 |
| ＞600 VA | 21.6 | 10.7 | 7.2 | 3.8 | 3.1 | 2 | 1 | 1 |

For larger (> 600 VA) DER, the impedance required to meet the limits 3≤h≤13 must be specified. A total distortion limit value covering 14≤h≤40 is also given and is in the range of 1-4% [18]. IEC 61000-3-6, IEC 61000-3-7, and IEC 61000-3-8 deal with installations, customarily those that consume energy. Modifications in next editions will consider energy producing installations. But IEC should use its fundamental premise that larger installations are allowed to create greater disturbances. In these documents , the definition of total system capacity can be changed in the future, it can be a combined function of the energy produced and the energy consumed. This function should include different weighting factors to the power generation vs. Power consumption.

For allocation procedure, the existing procedures look good, but some problems remain. The concept for the remaining procedures is based on the assumption that the system starts from a clean state, but the fact is that the state is not clean enough. Existing procedure can not handle with the case that the existing level is beyond the desired limit level. So, new allocations should only be based on the difference between what exists today and an established maximum level.

To conclude, there are still much ongoing work to do on DER power quality standards. IEEE 1547-2018 is the only established standard so far. However, new standards are based on the existing technology and assumptions, which is for energy consuming equipment and installations.

# CHAPTER 5. CONCLUSION

Through the comparison of harmonics, three-phase unbalance, and flicker standards for China, IEEE, and IEC, some brief conclusions can be made.

1) There is a significant difference in harmonic limits determined using these three standards. Not only the values, but the standard formulation is also different.

2) These three standards have relatively small differences in the requirements for three-phase unbalance, and these differences are mainly reflected in the numerical values.

3) In handling the flicker problem, all three standards adopt the IEC definitions of flicker problems and related standards for measurement and limit allocation.

4) The DER power quality standards are generally converging to the corresponding power quality standards for installations. Only under different conditions or environments, or given different factors, are there more stringent requirements for specific parameters.

The difference in formation between these three groups of standards can be attributed to the following reasons: Firstly, history and traditions are much different. The two predecessors of IEEE are AIEE (American Institute of Electrical Engineers) and IRE (Institute of Radio Engineers). IEC was founded in 1906 and has 112 years of history up to now. Many of the standards currently used are the updated versions and are under continuous improvement. However, China has less than 30 years of setting uniform standards. Compared to the Chinese standards, IEEE and IEC have a more complete standard-setting system, especially on the measuring and testing part.

Secondly, environmental differences between regions, including population, natural environment, economic level, etc, drive differences. Any standard should be formulated in accordance with the corresponding objective conditions. For example, China has more HV and EHV transmission lines due to the high population density in the eastern cities. Coupled with economic factors, Chinese standards become strict for the HV and EHV voltage levels while being more loose at the LV and MV levels.

For DER power quality standards, it can be seen that with the continuous development of distributed power technology, the corresponding standard requirements are constantly updated. No matter how the standards change, the overall trend will move toward making the power system more reliable and stable. The unification of standards is a key part of this task. It is hoped that different standards groups around the world will be able to communicate and develop more harmonized documents in the future.

## REFERENCES

[1]. *Electrical Power Systems Quality ( Third Edition)*, Roger C.Dugan, Mark F McGranaghan, Surya Santoso, H. Wayne Beaty.

[2]. IEEE Std 1543tm -2011, "IEEE Recommended Practice—Adoption of IEC 61000-4-15:2010,Electromagnetic compatibility (EMC)—Testing and measurement techniques—Flickermeter—Functional and design specifications".

[3]. GB/T 14549-93, "Quality of electric energy supply Harmonics in public supply network".

[4]. IEEE Std 519™-2014 (Revision of IEEE Std 519-1992) IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

[5]. IEC 61000-3-2 EMC Part3 Limits- Limits for Harmonic Current Emissions (equipment input current≤16 A per phase. )

[6]. IEC 61000-2-2 EMC Part 2-2: Environment-Compatibility Levels for Low Frequency Conducted Disturbances and Signalling in Public Low-Voltage Power Supply Systems.

[7]. IEC 61000-3-6 EMC part 3 Limit-Assessment of Emission Limits for Connection of Distorting Installations to MV, HV and EHV Power Systems.

[8]. GB/T 15543-2008, "Power quality--three-phase voltage unbalance".

[9],[13]. IEC 61000-3-13 Ed.1: Electromagnetic compatibility (EMC) – Part 3-13: Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems.

[11]. GB/T Std 12326-2008, "Power quality--voltage fluctuation and flicker".

[12]. IEEE Std 1453-2015, IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems.

[14]. IEC 61000-3-7 Ed.2: Electromagnetic Compatibility (EMC) – Part 3-7: Assessment of Emission Limits for the Connection of Fluctuating Load Installations to MV, HV and EHV Power Systems.

[15]. GB/T 19939-2005, “Technical requirements for grid connection of PV system”.

[16], [17]. IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.

[18] IEC 61000-3-16 (harmonics produced by DER equipment, less than 75 A)