Comparison of Chinese and International Harmonic, Interharmonic and Flicker Standards

by

Yao Wang

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
December 13, 2014

Key words: harmonic, interharmonic, voltage fluctuation and flicker, comparison

Approved by

Mark Halpin, Chair, Distinguished Professor of Electrical and Computer Engineering
Mark Nelms, Professor of Electrical and Computer Engineering
John Hung, Professor of Electrical and Computer Engineering

Abstract

Power quality is one of the essential problems related to daily life with growing quantities of power electronic equipment invading our homes, offices and factories. Standards for power quality, including harmonics, interharmonics, and voltage fluctuations and flicker, are the basic technical documents that apply in the power supply system, so it is worth making a comparison of these standards from different organizations. This entire thesis is around the centerpiece of three Chinese standards: GB/T 14549-93 for harmonics, GB/T 24337-2009 for interharmonics, and GB/T 12326-2008 for voltage fluctuations and flicker. This thesis firstly compares and analyzes the harmonic standards among GB/T 14549-93 and the other two most well-known standards – IEEE 519-1992 and IEC 61000-3-6:2008. Then discussion turns to the only independent interharmonic standard GB/T 24337-2009. At last, the comparison is conducted on two voltage fluctuation and flicker standards – GB/T 12326-2008 and the widely accepted IEC 61000-3-7:2008. Emission limits and the underlying basic principles are the primary concerns of this research.

Acknowledgments

I would like to express my gratitude to all those who helped me during the writing of this thesis. My deepest gratitude goes first and foremost to Professor Mark Halpin, my supervisor, for his constant encouragement and guidance. Without his illuminating instruction, this thesis could not have reached its present form. Second, I would like to express my heartfelt gratitude to all the professors who instructed and helped me a lot during classes in the past two years in the Department of Electrical and Computer Engineering. Last my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years.

Tables of Contents

List of Figures

List of Tables

Chapter 1

Introduction and Literature Review

1.1 Introduction

1.1.1 Power Quality

Power quality in the context of this thesis is the set of limits of electrical properties that determine the fitness of electric power for consumer devices. “Clean” power refers to power that has sinusoidal voltage and current without any distortion and operates at the designed magnitude and frequency. With growing quantities of power electronic equipment, for instance computers and microprocessors, invading our homes, offices and factories, utilities are responsible for offering high quality power to those sensitive loads. However, the end-user equipment is not only sensitive to “bad power quality,” but also some of the loads cause disturbances within the whole system and affect other customers. Industries have introduced energy-saving devices within the last several decades and that energy-saving equipment, like adjustable-speed drives, is often nonlinear loads which become the sources of poor power quality [1].

Utilities are in charge of the whole system power quality and they cannot neglect the disturbances caused by some of the end-users since it directly affects their competitiveness. So, they need to identify the customers who produce the problems and require them to fix them. Utilities and consumers need to have procedures that prevent power quality problems and the best way is to sign contracts which incorporate power quality standards established by standard organizations [2].

Power quality standards are necessary for the power industry. The electronics industry needs the standards to produce sensitive electronic equipment. The power conditioning industry needs standards to produce devices that will protect sensitive electronic equipment. Utilities need the standards to provide their customers good quality power and meanwhile restrain the customers' undesirable behavior. Therefore, voltage and current limits are set in the standards for sensitive electronic equipment. Utilities apply those limits on the voltage distortion to defend their power systems from damage produced by nonlinear installations. End users need those limits for electrical disturbances produced both by utilities and the other users. Hence, with the recognition that power quality standards become vital to the viability of the entire industry, several national and international organizations have developed standards aiming at different types of power quality problems.

Power quality problems can be divided into two types, namely continuous and event-based power quality problems. Continuous power quality problems refer to the voltage or current waveform, amplitude, frequency or phase angle having small variations over a long time scale. Monitoring these slight variations has to take place continuously. These power quality problems include voltage deviations, frequency deviations, voltage unbalance, harmonics, interharmonics and voltage fluctuations and flicker. On the contrary, event-based power quality problems are associated with the phenomenon of the voltage or current occasionally and significantly deviating from their normal or ideal wave shape. Event problems include voltage sags, voltage swells, temporary or transient over-voltage, short interruptions and long interruptions [2, 3]. Among these different types of power quality problems, harmonics, interharmonics and voltage fluctuations and flicker are certainly important in industry.

Harmonics relate to those spectral components of a periodic waveform characterized by frequencies that are integer multiples of the ac system fundamental frequency (60Hz/50Hz). Nonlinear loads, like adjustable speed drives, rectifiers and electronic office machines, are some of the sources of harmonics. The harmonic current caused by those nonlinear loads changes a sinusoidal current to a distorted waveform. When the distorted current flows through impedances, distorted voltages appear. The harmonic currents and voltages bring detrimental effects to both the utility and end-users. Harmonics may result in steady-state overvoltages or overcurrents which contribute to loss-of-life or immediate failures of transformers, power cables and motors.

Alternatively, interharmonics refer to spectral components of a periodic waveform at frequencies that are not integer multiples of the system fundamental frequency. Actually, most harmonic sources are also interharmonic sources, especially static frequency converters, cyclo-converters and arc furnaces. Just like some typical problems caused by harmonics, interharmonics also create problems such as overheating and useful life reduction. What's more, they can also create serious problems such as communication interference, voltage fluctuations and light flicker.

Voltage fluctuations refer to rapid changes in voltage magnitude, usually less than 5%-10% of the normal value. They are generally caused by devices like electric arc furnaces and welders. Common loads are rarely impacted by these voltage variations except for lighting load. Voltage fluctuations give rise to rapidly varying output from incandescent and sometimes other lights and the change in light intensity occurring at 6 to 8 Hz is easily seen by human eyes. This visual phenomenon perceived by our brain is known as "flicker." Since it directly affects everyday life of most people, complaints and irritations due to flicker problems will influence the competitiveness of power companies.

Considering the effects brought from harmonic, interharmonic and flicker problems, limits are set to constrain the behaviors of both customer and utilities by national and international standard organizations. Research institutions in China have also completed significant research on harmonics, interharmonics and voltage fluctuations and offer the corresponding rules based on the Chinese particular situation. Since China has become one of the largest developing countries because of their gradually wider communication with world's industries, it is worth making a comparison on those standards from China and other international organizations to get a better understanding of similarities and differences.

1.1.2 Standard Organizations

A. Standardization Administration of China (SAC)

The Standardization Administration of China (SAC) is in charge of the entire standard setting process in China. The Technical Committee (SAC/TC) is focused on technology standardization. Two sub-organizations - SAC/TC1 and SAC/TC246 - take charge of power quality standardization.

SAC/TC1 is short for Chinese National Standardization Technical Committee for Voltages, Current Ratings and Frequencies, which was established in 1987 as the first technical committee of SAC/TC. SAC/TC1 contributes to current, voltage and frequency standards. Also, it takes the responsibility of communicating with the International Electrotechnical Commission (IEC) Technical Committee (TC8). SAC/TC246 represents the Chinese National Standardization Technical Committee for Electromagnetic Compatibility started in 2000. This organization works on the aspects of electromagnetic compatibility and environment, and also manages the communication with IEC/TC77. Its main duty is to transform parts of the IEC 61000 standards into Chinese versions, including power quality, emission limits, immunity tests, measurement techniques etc.

Chinese standards can be divided into three types – GB and GB/T, and one more type GB/Z added recently. GB refers to compulsive standards applied in China to protect health and property safety and are implemented by law. GB/T standards are the recommended standards used in the process of production and application and they are not executed by law until both customers and industries reach agreement for their adoption. Any company has the right to decide whether to adopt GB/T and does not need to take economic responsibility. GB/Z refers to guiding technical documents which are compliments to standards GB and GB/T. These types of documents can be used for technical support during production and application, but they are not guaranteed or constrained by law even when enterprises and customers make their contracts. Attention should be paid to the date problem existing in titles of standards. GB standards without the date labeled are taken as using the newest version, while GB/T and GB/Z standards with the year in their title should be regarded as fixed.

B. International Electrotechnical Commission (IEC)

The International Electrotechnical Commission (IEC) is the world leading, non-profit, non-government organization that prepares and publishes International Standards for all electrical, electronic and related technologies. Founded in 1906, it provides the platform for stakeholders of every nation and over 10,000 experts from industry and government to participate in discussions about the international standards they require.

The basic concept in the IEC standards is electromagnetic compatibility (EMC) which is defined as “the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.” The two aspects of EMC are "immunity" that is defined as "ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance," and "emission" that is defined as "phenomenon by which electromagnetic energy emanates from a source of electromagnetic disturbance" [4]. The concepts of compatibility level and planning level are developed related to emission problems. Compatibility level refers to reference values for coordinating emission and immunity of the equipment in the whole system and it is chosen based on 95% probability levels of entire systems. Planning levels are deemed to be the internal quality objectives for the utility and specified by the supply system owner or operator. Their relationship can be illustrated in Figure 1.1 [5].

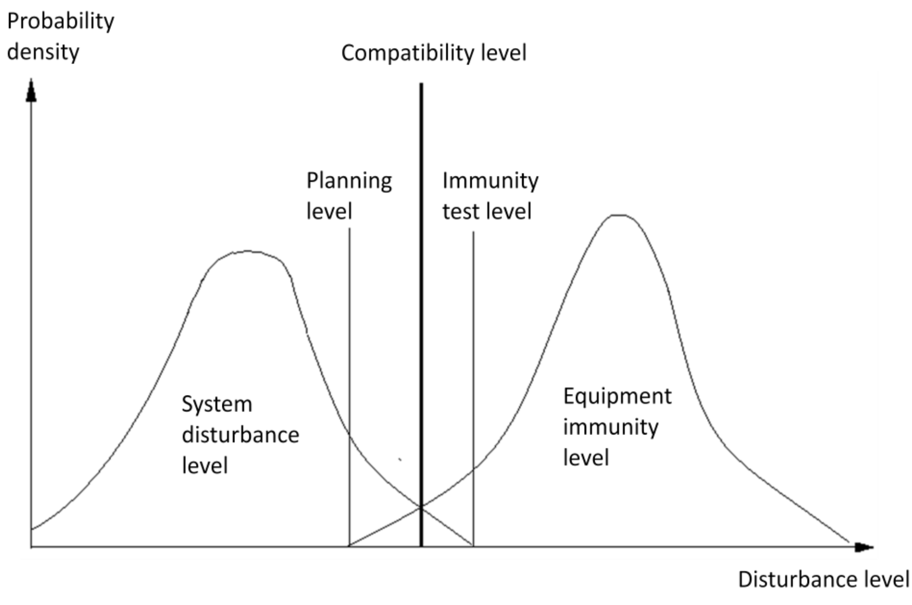

Figure 1.1 Illustration of Different Levels

IEC standards cover a vast range of technologies from power generation, transmission and distribution to semiconductors, solar energy, batteries and many others. Power quality standards are prepared by sub-committee SC77A and Working Group 8 takes charge of standards and technical reports that apply to the interface of the supply system.

C. Institute of Electrical and Electronic Engineers (IEEE)

The Institute of Electrical and Electronic Engineers is a not-for-profit association founded in 1963 and incorporated from two organizations: the American Institute of Electrical Engineers (AIEE) and the Institute of Radio Engineers (IRE). It has become one of the largest professional organizations in the world and has more than 425,000 members from 160 countries. The IEEE includes 38 technical societies, organized around specialized technical fields. It also serves as a major publisher of scientific journals and organizer of conferences.

With nearly 1,300 standards and projects under development, IEEE is one of the leading standards-making organizations in the world. The IEEE Standards Association (IEEE-SA) works on the standardization activities of the IEEE. IEEE standards affect a wide range of industries including power and energy, biomedical and healthcare, information technology, information assurance, telecommunications, transportation, and many more.

1.2 Scope of This Research

The entire research consists of three parts:

- Comparing and analyzing harmonic standards among Chinese standard GB/T 14549-93 and international standards IEC/TR 61000-3-6:2008 and IEEE

Std. 519-1992;

- Analyzing the Chinese interharmonic standard GB/T 24337-2009; and

- Comparing and analyzing the voltage fluctuation and flicker standards Chinese standard GB/T 12326-2008 and the international standard IEC/TR 61000-3-7:2008.

Chapter 2

Harmonic Standards

2.1 Introduction

2.1.1 Background

The requirements in harmonic standards vary across HV-EHV, MV, and LV systems according to nominal voltage levels. Based on the application area, harmonic standards are also divided into equipment level and system level. The equipment standards define the limits for individual equipment harmonic current emissions, while the system standards deal with the connection of customers having large harmonic-producing loads to supply systems.

Regarding harmonic emission limits for equipment, the widely recognized international standards are IEC 61000-3-2:2004 [6], IEC 61000-3-4:1998 [7], and IEC 61000-3-12:2004 [8]. IEC 61000-3-2:2004 applies to electrical and electronic equipment whose input current is lower than 16A per phase in LV networks. Four classes of equipment harmonic current emissions are considered with individual harmonic limits given up to the 40^{th} order. IEC 61000-3-4:1998 covers connection of equipment with a current rating more than 16A to a supply system. This standard deals with individual equipment and system installation and considers three consecutive assessment stages. Both single-phase and three-phase harmonic limits are addressed. IEC 61000-3-12:2004 is applicable to electrical equipment within the range of 16A and 75A and discusses the limitation of harmonic currents injected into the public system [9].

At the system level, IEC, IEEE and SAC/TC provide the corresponding standards for low, medium and high/extra-high voltage systems. LV system standards include IEC 61000-2-2:2002 [10], GB/T 14549-93 [11] and IEEE 519-1992 [12], while GB/T 12549-93 and IEEE 519-1992 also apply to the MV and HV/EHV supply systems as does IEC 61000-3-6:2008. IEC 61000-2-2:2002 defines the compatibility level of voltage distortion in LV systems. IEC 61000-3-6:2008 provides indicative planning levels for harmonic voltages in MV, HV and EHV power system. Both GB/T 14549-93 and IEEE 519-1992 set the current and voltage distortion limits at the point of common coupling. One more thing that should be noted is that SAC/TC246 has transformed several IEC standards into Chinese versions which are adopted as technical direction documents. For instance, IEC 61000-3-6:1996 is used as GB/Z 17625.4-2000 and the GB/Z 17625.6-2003 comes from IEC 61000-3-4:1998. Since utility application is the concern of this research, only GB/T 14549-93, IEEE 519-1992 and IEC 61000-3-6:2008 will be analyzed and compared.

2.1.2 GB/T 14549-93

The first edition of Chinese harmonic standard SD126-84 was drafted on the basis of UK standard G5/3 in 1984 and used as the provisional standardization file. With widespread investigation of harmonic levels across the nation, SAC/TC1 published GB/T 14549-93 in 1994 which has been used for 20 years. This standard consists of three major parts: terminology illustration, harmonic limits and measurement. The application extent of GB/T 14549-93 is to systems with rated frequency of 50Hz and any voltage level under 220kV. GB/T 14549-93 provides the harmonic voltage distortion limits in percent of phase voltage U_1 in Table 2.1 for commonly used public system voltage levels.

Bus Rated Voltage U_N (kV)	Total Voltage Distortion (%)	Individual Voltage Distortion in % of U_1	
		Odd Order	Even Order
0.38	5.0	4.0	2.0
6	4.0	3.2	1.6
10			
35	3.0	2.4	1.2
66			
110	2.0	1.6	0.8

Table 2.1 Voltage Harmonic Limits (GB)

Considering the heating problem of the AC induction motor, the over-voltage and over-current endurance ability of capacitors and electronic computers and the requirements of solid-state relay protection, the LV voltage THD limit is set at 5%. Medium and high voltage level THD limits are set on the foundation of the 380V voltage harmonic THD value after analyzing typical national power grid structures and the transfer coefficients from upstream systems to the next voltage levels.

GB/T 14549-93 introduces a summation law for two or more harmonic sources encountered at one point.

$$U_h = \sqrt{U_{h1}^2 + U_{h2}^2 + K_h U_{h1} U_{h2}} \quad (2.1)$$

In (2.1),

U_{h1} : the harmonic voltage of order h from harmonic source 1,

U_{h2} : the harmonic voltage of order h from harmonic source 2, and

K_h : the summation coefficient.

When applying the values in Table 2.1 in practice, the voltage limits in the GB standard should be recalculated with consideration of the transfer coefficient from the upstream system by combining the summation law in (2.1) and the original values in Table 2.1. The required harmonic value in one system is expressed as a function of the harmonic sources from its own voltage level and the upstream effect from a higher voltage level as shown in (2.2). Assuming the transfer coefficient T equals 0.8 and the summation coefficient K_h equals 1, the equation for calculation becomes (2.3). Considering the overvoltage of installations due to the magnification of the 3rd harmonics in a supply system, the individual voltage distortion limits for them are defined to be 60% of the non-multiple of 3 odd harmonic values.

$$U_{hL} = \sqrt{U_{hd}^2 + (TU_{hH})^2 + K_h U_{hd}(TU_{hH})} \quad (2.2)$$

$$U_{hd} = \sqrt{U_{hL}^2 - 0.48U_{hH}^2} - 0.4U_{hH} \quad (2.3)$$

In (2.2) and (2.3),

T : the transfer coefficient,

U_{hd} : the value of the voltage distortion limit at the required voltage level for the h^{th} harmonic,

U_{hL} : the voltage harmonic limit of the required voltage level from Table 2.1 for the h^{th} harmonic, and

U_{hH} : the voltage harmonic limit of the upstream level from Table 2.1 for the h^{th} harmonic.

The results of applying (2.3) to the values in Table 2.1 are shown in Table 2.2. These values represent the total allowable contribution of all loads at each voltage level. The values shown in Table 2.2 include the total voltage distortion and individual voltage distortion (HRU_h) in percent of system phase voltage U_1.

Bus Rate Voltage U_N (kV)	Total Voltage Distortion %	Individual Voltage Distortion (HRU_h) in % of U_1		
		Odd Order		Even Order
		Non-multiple of 3	Multiple of 3	
0.38	2.56	2.05	1.230	1.02
6	2.22	1.77	1.062	0.89
10				
35	1.86	1.49	0.894	0.74
66				
110	1.50	1.20	0.720	0.60

Table 2.2 Different Voltage Level Harmonic Limits (GB)

The allowable value of current injected into the supply system is a function of equivalent impedance and the voltage limit at each of the harmonic frequencies. Voltage limits used for current emission limits calculation are obtained from HRU_h values in Table 2.2 considering upstream effects. By putting into use (2.4) and Table 2.2, current harmonic emission limits shown in Table 2.3 and Table 2.4 can be derived.

$$I_h = \frac{10 S_{sc} HRU_h}{\sqrt{3} U_N h} \tag{2.4}$$

In (2.4) and Table 2.2,

S_{sc} : the three phase short circuit capacity at PCC in MVA,

U_N : the nominal system voltage (line-to-line) in kV,

h : the harmonic order,

I_h : the harmonic current of order h in A, and

HRU_h: the individual harmonic voltage distortion in percent of phase voltage U_1 of order h provided in Table 2.2.

Bus Rated Voltage U_N (kV)	Short Circuit Capacity Reference S_{sc} (MVA)	Harmonic Order and Current Harmonic Allowable Values I_h (A)								
		2	3	4	5	6	7	8	9	10
0.38	10	77.49	62.29	38.74	62.29	25.38	44.50	19.37	20.76	15.50
6	100	42.82	34.06	21.41	34.06	14.27	24.33	10.71	11.35	8.56
10	100	25.69	20.44	12.85	20.44	8.56	14.60	6.42	6.81	5.14
35	250	15.26	12.29	7.63	12.29	5.09	8.78	3.81	4.10	3.05
66	500	16.18	13.03	8.09	13.03	5.39	9.31	4.05	4.34	3.25
110	750	11.81	9.45	5.90	9.45	3.94	6.75	2.95	3.15	2.36

Table 2.3 2nd-10th Allowable Harmonic Current Values (GB)

Bus Rated Voltage U_N (kV)	Short Circuit Capacity Reference S_{sc} (MVA)	Harmonic Order and Current Harmonic Allowable Values I_h (A)									
		11	12	13	14	15	16	17	18	19	20
0.38	10	23.32	12.91	23.96	11.07	12.46	9.69	18.32	8.61	16.39	7.75
6	100	15.48	7.14	13.10	6.12	6.81	5.35	10.02	4.76	8.96	4.28
10	100	9.30	4.28	7.86	3.67	4.09	3.21	6.01	2.85	5.38	2.57
35	250	5.59	2.54	4.73	2.18	2.46	1.91	3.61	1.70	3.23	1.53
66	500	5.92	2.70	5.01	2.31	2.61	2.02	3.83	1.80	3.43	1.62
110	750	4.29	1.97	3.63	1.69	1.89	1.48	2.78	1.31	2.49	1.18

Table 2.4 11^{th}-20^{th} Allowable Harmonic Current Values (GB)

2.1.3 IEEE Std. 519-1992

IEEE Std. 519-1992 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems” was prepared by a joint task force sponsored by several IEEE organizations to supersede the first edition IEEE Std. 519-1982. As a quite mature document which has been adopted by most North American utility companies, it provides explicit harmonic current and voltage limits that are listed separately from Table 2.5 to Table 2.8. This recommended practice recognizes the responsibility that users have to obey current injection limits and also the obligation that utilities have of making sure a clean sine wave voltage is provided at the point of common coupling (PCC) for all users.

Maximum Harmonic Current Distortion in Percent of I_L						
I_{sc}/I_L	< 11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2.5 120V-69kV Current Distortion Limits (IEEE)

Maximum Harmonic Current Distortion in Percent of I_L						
I_{sc}/I_L	< 11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	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	4.0
$50 < 100$	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

Table 2.6 69kV-161kV Current Distortion Limits (IEEE)

Maximum Harmonic Current Distortion in Percent of I_L						
I_{sc}/I_L	< 11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
< 50	2.0	1.0	0.75	0.3	0.15	2.5
> 50	3.0	1.5	1.15	0.45	0.22	3.75

Table 2.7 >161kV Current Distortion Limits (IEEE)

The following definitions apply in Tables 2.5-2.7:

h : the harmonic order,

I_{sc} : the maximum short-circuit current at the PCC, and

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

Current limits recommended for individual customers are developed to achieve the voltage goal with maximum individual harmonic voltage levels of no more than 3% and THD no more than 5% for voltages at the PCC less than 69kV. This accounts for diversity for different loads including different harmonic components and phase angles, and partially considers the resonance problem. A summation law is not explicitly considered.

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
$\leq 69\text{kV}$	3.0	5.0
$69\text{kV} - 161\text{kV}$	1.5	2.5
$\geq 161\text{kV}$	1.0	1.5

Table 2.8 Voltage Distortion Limits (IEEE)

2.1.4 IEC 61000-3-6:2008

The second edition of IEC 61000-3-6 issued in 2008 is an update of the IEC harmonic emission limits guide for MV and HV/EHV systems published in 1996 [13]. As the concept of compatibility level and planning level are introduced in the first chapter, only indicative planning levels for harmonic voltages of MV and HV-EHV are given in IEC 61000-3-6:2008 which are shown in Table 2.9.

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even		
Harmonic Order h	Harmonic Voltage, %		Harmonic Order h	Harmonic Voltage, %		Harmonic Order h	Harmonic Voltage, %	
	MV	HV-EHV		MV	HV-EHV		MV	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
$17 \leq h \leq 49$	$1.9 \cdot \frac{17}{h} - 0.2$	$1.2 \cdot \frac{17}{h}$	$21 \leq h \leq 45$	0.2	0.2	$10 \leq h \leq 50$	$0.25 \cdot \frac{10}{h} + 0.22$	$0.19 \cdot \frac{10}{h} + 0.16$
$THD_{MV} = 6.5\%,\ THD_{HV-EHV} = 3\%$								

Table 2.9 Planning Levels for Harmonic Voltage (IEC)

Current emission limits are set dependent on the agreed power of the customer, the power of the harmonic-generating equipment, and the system characteristic. The objective is to limit the harmonic injection from the total of all distorting installations to levels that will not violate the voltage planning level. Three stages are given in IEC 61000-3-6:2008 to evaluate installations connecting into the public supply system. Stage 1 accepts small device installations which satisfy the relevant requirements based on a simplified evaluation of disturbance emission. Stage 2 allots absorption capacity proportionally to individual loads who do not meet stage 1 criterion while taking into account the transfer factors from upstream voltage levels. Stage 3 agrees on disturbances emission limits beyond stage 2 and considers all known specifics of the situation in detail.

2.2 Comparison

Several documents have contributed to the comparative analysis between

IEC 61000-3-6 and IEEE 519-1992 [14, 15]. Due to the problems appearing during the decades when launching GB/T 14549-93 worked out by SAC/TC1, the Chinese standardization organization announced the revision instruction in 2006. Before the new edition of GB standard comes out, a comparison between the GB harmonic standard and the two most well-known international harmonic standards can make our understanding better.

2.2.1 Application

A. Scope

The harmonic distortion limit from GB/T 14549-93 whose specific scope is 50Hz frequency and rated voltage under 220kV covers LV, MV and HV systems without any consideration of EHV supply systems. This standard only applies under normal operation excluding transient conditions. Short duration harmonics are not addressed in detail except for the terminology explanation.

IEEE 519-1992 intends to establish harmonic limits for nonlinear loads throughout the system under steady-state conditions and are recommended for the “worst case” situation. The standard covers almost all voltage levels, but it specifically excludes high-voltage direct current (HVDC) facilities and static var control (SVC) systems operated by utilities under certain conditions. The steady-state limits may be exceeded under short-term conditions. These conditions are considered with an allowable value of twice the ordinary steady-state limits.

The objective of IEC 61000-3-6:2008 is to provide the guidance and basis for determining the requirements of connecting distorting installations to MV, HV and EHV public power systems. This technical report use the following boundaries for system voltages: $\mathrm{U_N} \leq 1\mathrm{kV(LV)}$, $1\mathrm{kV} < U_\mathrm{N} \leq 35\mathrm{kV(MV)}$, $35\mathrm{kV} < U_\mathrm{N} \leq 230\mathrm{kV(HV)}$ and $230\mathrm{kV} < U_\mathrm{N}\mathrm{(EHV)}$. All the reference values of planning levels and compatibility levels provided in this IEC standard relate to long-term effects that may exist for 10 min or more. The values for less than 3s (short-term effects) are determined from the long-term values multiplied by a factor $\mathrm{k_{hvs}}$ as shown in (2.5).

$$k_{hvs} = 1.3 + \frac{0.7}{45} \cdot (h - 5) \quad (2.5)$$

B. Indices

Good harmonic indices are characterized as “physically meaningful,” “strongly correlated to the severity of the harmonic effects,” “possible to determine by measurements” and “simple and practical,” as quoted from IEEE 519-1992. Although the basic indices for the three standards are of four types - individual harmonic voltage and current limits, and total harmonic voltage and current distortion limits - the different use of terminology and concepts in the three standards gives rise to distinct evaluation procedures for harmonic distortion limit assessment. The relationship and comparison of the indices existing in the three standards are shown in Table 2.10.

IEC 61000-3-6:2008	IEEE 519-1992	GB/T 14549-93
Compatibility Level	×	×
Planning Level	×	Voltage Harmonic Limits
Global Harmonic Voltage Limits	Voltage Distortion Limits	
Voltage Emission Limits	Maximum Individual Harmonic Voltage	×
Current Emission Limits	Current Distortion Limits	Allowable Harmonic Current Values

Table 2.10 Comparison of Indices from the Three Standards

C. Points of Measurement

Measurement points in the three standards are defined with slight differences. GB/T 14549-93 regards the measurement point as the point of common coupling (PCC) explained as the interface between the customer and the public power system. The Recommended Practice IEEE 519-1992 attempts to establish the distortion limits at the PCC which is defined as “a point of metering, or any point as long as both the utility and the consumer can either access the point for direct measurement of the harmonic indices or can estimate the harmonic indices at a point of inference (POI) through mutually agreeable methods.” The assessment of emission levels for a customer’s installation in IEC 61000-3-6:2008 is at the point of evaluation (POE), which could be “the point of connection (POC) or the point of common coupling (PCC) of the disturbing installation or any other point specified by the system operator or owner or agreed upon.” Owing to the diversity of definitions given for the measurement points, misapplication could happen when applied in reality, which is described specifically in [16].

D. Summation Law

More than one harmonic producing installation connected to one measurement point gives rise to voltage or current summation. Therefore, the actual voltage at one point or current through one branch is the sum of individual components from each disturbance source. For example, the wave shape of the harmonic current from one converter will not be synchronous with that from another converter because the wave shape is determined by the delay angle or overlap angle during the commutation process. Thus, vector summation becomes unavoidable for accurate results.

GB/T 14549-93 introduces a summation law for two or more harmonic currents encountered at one point. Two harmonic components at one frequency can be added using (2.6) provided that the phase angle is known, otherwise (2.7) will be used. Multiple harmonic component summation can be manipulated on the basis of combination results from two harmonic sources by applying the same law.

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + 2I_{h1}I_{h2}cos\theta_h} \tag{2.6}$$

$$I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + K_h I_{h1} I_{h2}} \tag{2.7}$$

In (2.4) and (2.5),

I_{h1} : the harmonic current of order h from harmonic source 1,

I_{h2} ： the harmonic current of order h from harmonic source 2,

θ_h : the phase angle difference between harmonic current of order h from harmonic source1 and source 2, and

K_h ： the summation coefficient shown in Table 2.11.

h	3	5	7	9	11	13	>13	even
K_h	1.62	1.28	0.72	0	0.18	0.08	0	0

Table 2.11 Summation Coefficients K_h (GB)

IEC 61000-3-6:2008 describes the summation law in (2.8). The indicative values of summation exponents for harmonics in (2.8) which are shown in Table 2.12 have been set taking account of the characteristics of sources, low order odd harmonics and high order harmonics.

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \qquad (2.8)$$

In (2.8),

U_{hi} ： the magnitude of the various individual emission levels of order h, and

α ： the summation exponents for harmonics.

Harmonic order	α
$h < 5$	1
$5 \leq h < 10$	1.4
$h > 10$	2

Table 2.12 Summation Exponents α (IEC)

There is no summation law described in IEEE 519-1992. Circuit analysis using the principle of superposition gives an approximate result, but only for simulations.

2.2.2 Philosophy

The first distinction between the three standards is that two of them provide both harmonic voltage and current limits, while the third only provides indicative voltage limits. So-called “indicative” limits are general recommendations which could be modified to meet the needs of particular situations. Despite their common goal to set limits for disturbing installations connected to the public supply system, this distinction is driven by their different application philosophy. By evaluating their analysis processes, the differences between their driving principles can be readily captured.

GB/T 14549-93 obtains voltage harmonic limits based on consideration of other international standards and experience in combination with Chinese specific circumstances. The harmonic current limits are a function of the system impedance and the voltage limit accounting for the effects from the upstream system. Current limits calculated from the voltage limits are allocated fairly according to the size of a customer to restrict the harmonic injection level. Thus, both current and voltage limits are pre-calculated and provided in the GB standard. In theory (assuming a linear system impedance and accurate transfer coefficients), if all the loads are within their injection limits, voltage quality could be guaranteed within the entire system. However, it may not quite meet the theory in reality due to the pre-calculated ideal current emission limit. Therefore, both the power company and the customers are obligated to maintain good voltage quality.

The philosophy of IEEE 519-1992 is stated as “(1) limit the harmonic injection from individual customers so that they will not cause unacceptable voltage distortion levels for normal system characteristics” and “(2) limit the overall harmonic distortion of the system voltage supplied by the utility.” In order to achieve this goal, voltage limit values are designed for the “worst case” in normal operation and the harmonic current limits are developed based on the maximum individual frequency harmonic voltage caused by a single load and the short-circuit impedance. Accordingly, with the voltage distortion limits and pre-calculated current distortion limits provided, the fundamental IEEE philosophy is a “shared responsibility.” So, when individual users meet the current distortion limits, while the voltage distortion limits are violated, the probable reason is the magnification of harmonic current caused by resonance conditions. The utility should then take action like designing a harmonic filter to control and limit the voltage distortion.

IEC 61000-3-6:2008 describes its responsibility as the co-operation between customer and utility provided that the customer must maintain harmonic current emissions below the limits and the utility is in charge of the overall co-ordination. Instead of providing both voltage and current distortion limits, the IEC standard only gives indicative values for voltage planning levels. The current emission limits will be more system dependent in order to guarantee (to the extent possible) the voltage distortion agrees with the planning level. In order to achieve the voltage quality goal, coordination of limits becomes essential. Hence, the general principle for IEC 61000-3-6:2008 is to limit the harmonic injection from all disturbance installations to ensure the voltage quality.

2.2.3 Harmonic Voltage Limits

As stated in Table 2.8, the comparative analysis will be conducted among global harmonic voltage limits from IEC 61000-3-6:2008, voltage distortion limits from IEEE 519-1992 and voltage harmonic limits from GB/T 14549-93. Conceptual differences between voltage distortion management approaches will be discussed here.

A. Concepts

(1) global harmonic voltage limits (IEC)

Based on the planning level and summation law, it is necessary to consider all contributions to the voltage distortion in the system. The actual harmonic voltage in a system is not only from the distorting installations directly connected to any voltage level, but also coming from the upstream system. In a MV system, the relationship between the relevant factors including planning level, global harmonic voltage contribution and transfer coefficient are displayed in Figure 2.1 and calculated by (2.9).

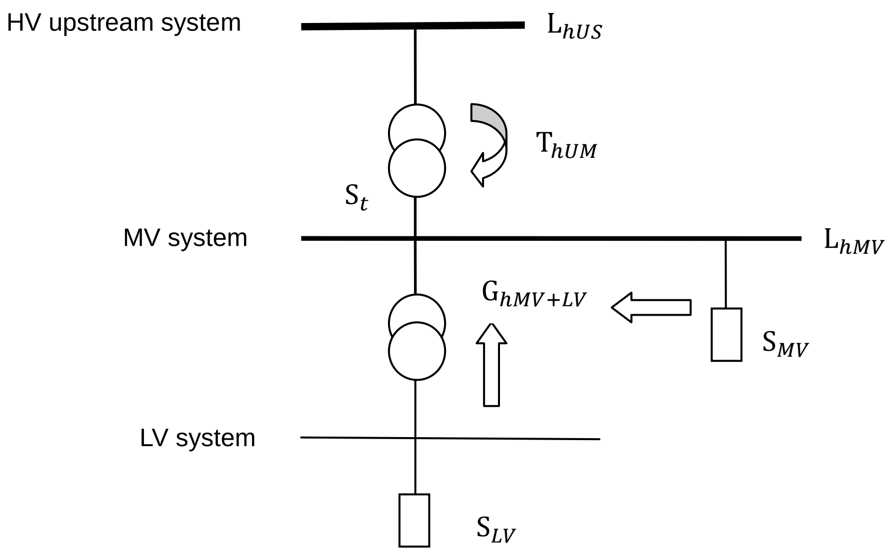

Figure 2.1 Sharing Global Contributions in a MV System

$$G_{hMV+LV} = \sqrt[\alpha]{L_{hMV}^{\alpha} - (T_{hUM} \cdot L_{hUS})^{\alpha}} \tag{2.9}$$

In (2.9) and Figure 2.1,

G_{hMV+LV}: the maximum global contribution of the total MV and LV installations that can be supplied from the MV busbar at the h^{th} harmonic in the MV system,

L_{hMV} : the planning level of the h^{th} harmonic in the MV system,

L_{hUS} : the planning level of the h^{th} harmonic in the upstream system,

T_{hUM} : the transfer coefficient of harmonic voltage of order h from the upstream system to the MV system,

S_t : the total supply capacity of the supply system,

S_{LV} : the total power of the installations supplied directly at LV in the supply system, and

S_{MV} : the total power of the installations supplied directly at MV in the supply system.

(2) Voltage harmonic limits (GB)

Voltage harmonic limits given in GB/T 14549-93 can be regarded as a combination concept of the global harmonic voltage limit and the planning level in IEC 61000-3-6:2008. Compared to the voltage harmonic limits offered at independent voltage levels in the GB standard, the planning level in the IEC standard may need to be allocated if there are several voltage levels within one system. However, applying GB voltage harmonic limits in practice will require more calculations considering the transfer coefficient when compared to the global harmonic voltage limit concept given in the IEC standard.

(3) Voltage distortion limits (IEEE)

The voltage distortion limits from IEEE 519-1992 can be compared directly with the values of global harmonic voltage limits from the IEC standard.

B. Comparison

Some notations should be made before the comparison shown in Table 2.13 is considered:

∗ The scope for comparison covers only MV systems.

∗ The global contribution value for harmonic voltage is calculated by equation (2.7) when assuming the planning levels in the HV and MV system are from Table 2.7 and the transfer coefficient from the upstream HV system is equal to 1 at all harmonic frequencies.

∗ The voltage limits in the GB standard should be recalculated with consideration of the transfer coefficient from the upstream system. So, the values for comparison should be those in the Table 2.2.

∗ The comparison is for a voltage level of 6-10kV and for harmonic orders from 5 to 20.

Harmonic Order	Odd, %				Even, %			THD %
	5	7	11	13	2	4	6	
GB/T 14549-93	1.8	1.8	1.8	1.8	0.9	0.9	0.9	2.2
IEEE Std.519-1992	3	3	3	3	3	3	3	5
IEC 61000-3-6:2008	4	2.8	2.6	2	0.4	0.2	0.2	4.9

Table 2.13 6-10kV Voltage Harmonic Limits Comparison

Voltage harmonic limits at 6-10kV, which belong to the MV system category, are obviously different in three standards. Two conclusions can be drawn from Table 2.13:

(1) The IEC standard provides unique harmonic voltage distortion values for each harmonic frequency while the IEEE standard gives the same value for every harmonic order. The GB standard only makes a distinction between odd order and even order harmonics.

(2) Compared to limits from the IEC standard and the IEEE standard, distortion limit values are more strict in the GB standard. A possible reason is that both IEC and IEEE standards are more intended to be international recommendation documents rather than aiming to be specific to one country.

2.2.4 Harmonic Current Limits

Three quantities with similar definitions mentioned in Table 2.8 – the allowable harmonic current value from GB/T 14549-93, the emission limit from IEC 61000-3-6:2008, and the current distortion limit from IEEE 519-1992 – will be discussed.

A. Concepts

(1) Harmonic current allowable value (GB)

The harmonic current allowable value in GB/T 14549-93 is derived from the voltage limit with consideration of the transfer coefficient from the upstream system and the harmonic impedance. The current limits in Tables 2.3 and 2.4 are given in the form of actual values under basic short-circuit capacity at different voltage levels. If the minimum short-circuit capacity at the PCC is not identical to what is given as the basic capacity, the allowable harmonic limit can be corrected using (2.10). The harmonic current allowable value for an individual customer i at harmonic order h is calculated by (2.11).

$$I_h = \frac{S_{sc}}{S_{scb}} I_{hb} \tag{2.10}$$

$$I_{hi} = I_h (S_i/S_t)^{1/\beta} \tag{2.11}$$

In (2.10) and (2.11),

I_h : the actual current limits of order h,

I_{hb} : the basic current limits of order h provided in Tables 2.3 and 2.4,

S_{sc} : the actual short-circuit capacity at the PCC,

S_{scb}: the basic short-circuit capacity at the PCC provided in Tables 2.3

and 2.4,

S_i : the agreed power demand of customer installation i,

S_t : the total supply capacity at the PCC, and

β : the phase coefficient from Table 2.14.

h	3	5	7	9	11	13	>13	even
β	1.1	1.2	1.4	2	1.8	1.9	2	2

Table 2.14 Phase Coefficients β (GB)

(2) Current distortion limit (IEEE)

IEEE 519-1992 establishes the maximum allowable current distortion for one customer by using the total demand distortion (TDD), which is expressed as the harmonic current distortion in percent of the maximum demand load current I_L. Similarly, the individual distortion limit is provided in percent of I_L as shown in Tables 2.5 - 2.7.

(3) Current emission limit (IEC)

Two approaches are presented for the current emission limit for each end-user in stage 2. The first approach uses “relative harmonic currents,” which is similar to the IEEE method. Indicative values for some odd order harmonic current emission limits relative to the size of a customer installation are provided in Table 2.15. This method is only for customers with an agreed power $S_i \leq 1\text{MVA}$, $S_i/S_{sc} < 1\%$ and no power factor correction capacitors, where S_i refers to the agreed power of a customer and S_{sc} refers to the short-circuit capacity at PCC.

Harmonic order h	5	7	11	13	>13
Harmonic current emission limit $E_{lhi} = I_{hi}/I_i$ (%)	5	5	3	3	$\frac{500}{h^2}$

Table 2.15 "Relative" Harmonic Current Emission Limits (IEC)

In Table 2.15,

E_{lhi} : the harmonic current emission limit of order h for customer i,

I_{hi} : the harmonic current of order h caused by the distorting installation of customer i, and

I_i : the r.m.s. current corresponding to the agreed power of customer i.

The second approach is the global distribution method. In this detailed method, the current emission limits are more rigorously derived from voltage distortion limits and the system impedance characteristics.

B. Comparison

Although the methods for developing current limits are different in the three standards, approximate comparisons can be made for some values. Direct value comparisons can only be made between current distortion limits in IEEE and current emission limits based on "relative harmonic currents" from IEC.

(1) Values of current limits:

The condition of applying "relative harmonic currents" in the IEC standard is that the customer should satisfy $S_i/S_{sc} < 1\%$, which is equivalent to the short-circuit ratio $SCR > 100$ in the IEEE standard. Hence, comparative values at odd harmonic frequencies in MV systems from Tables 2.3, 2.4 and 2.15 are shown in Table 2.16. It can be concluded that the current limits given in IEEE 519-1992 are less restrictive than the values provided by IEC 61000-3-6:2008.

Harmonic current, %	SCR	Individual Harmonic Order (Odd)				
		5	7	11	13	$17 \leq h < 23$
IEEE 519-1992	$100 < 1000$	12	12	5.5	5.5	5.0
	> 1000	15	15	7.0	7.0	6.0
IEC 61000-3-6:2008	> 100	5	5	3	3	$\frac{500}{h^2}$

Table 2.16 Current Harmonic Limits Comparison

(2) Even-order harmonics

The allowable values for harmonic currents in the GB standard consider even-order harmonics specifically by offering independent values for each even-order harmonic frequency under the 20^{th}. The IEEE standard recommends that the limits of the even-order harmonic should be 25% of the odd harmonic limits within the corresponding range. The IEC may allow greater emission of even-order harmonics in the applicable second approach because the current limit depends on each unique system characteristic.

(3) Characteristic harmonics

Characteristic harmonic components vary in every piece of equipment. For instance, the characteristic harmonics of a 6-pulse converter include the 5^{th}, 7^{th}, 11^{th} and 13^{th}, while the 11^{th} and 13^{th} are the lowest order characteristic harmonics of a 12-pulse converter. The converter, in theory, will not produce non-characteristic harmonic components. Nevertheless, in many cases, the non-characteristic harmonics will be large enough that their limits should also be formulated to ensure and maintain good power quality. Harmonic limits in the three standards are established in a general sense without consideration of characteristic harmonics. However, IEEE 519-1992 does provide some distinction between characteristic and non-characteristic harmonics. All current distortion limits in the IEEE standard are based on 6-pulse rectifier characteristic harmonics and the general distortion situation. When non-characteristic harmonics are less than 25% of the applicable limit, the limits for characteristic harmonics may be increased by a factor $\sqrt{\frac{q}{6}}$ where q is the pulse number of the converters being used.

2.2.5 Impedance

A. GB/T 14549-93

The harmonic current allowable value in GB/T 14549-93 is derived from the voltage limit with the consideration of transfer coefficients from the upstream system and the system harmonic impedance. The harmonic impedance Z_h for calculation is simply represented as the fundamental system reactance X_1 multiplied by the harmonic order h which is $Z_h = hX_1$. Accordingly, the relationship between harmonic order and harmonic impedance is linear as shown in Figure 2.2.

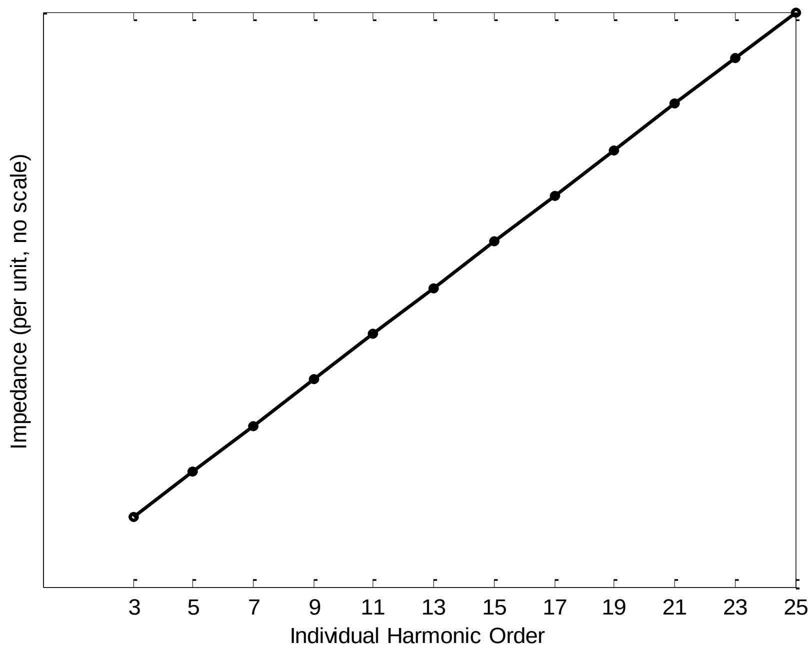

Figure 2.2 Harmonic Impedance in GB 14549-93

B. IEEE 519-1992

The current distortion limit is pre-calculated in IEEE 519-1992, but the impedance is still indispensable during power system analysis. The current distortion level given for individual consumers can be developed as a function of the maximum individual frequency harmonic voltage caused by a single end-user and the short-circuit impedance. The impedance could also be developed considering the diversity for different customers and the resonance phenomenon. Hence, the general and approximate value of impedance for analysis can be obtained roughly from the maximum individual frequency harmonic voltage divided by the current distortion limits. The results for short-circuit ratios below 20 and within the range 20 to 50 are shown in Figure 2.3 where the maximum individual frequency voltage harmonic is 3% of the fundamental.

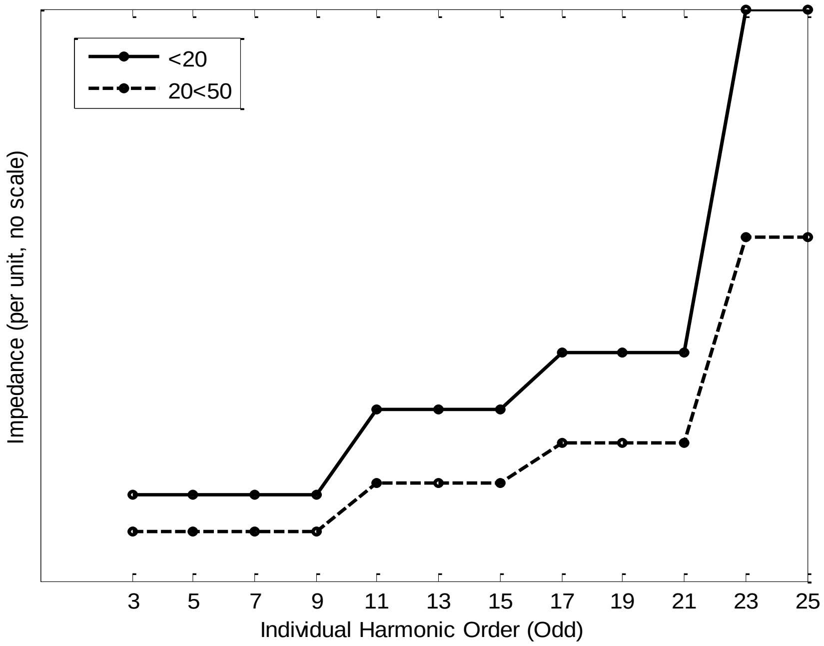

Figure 2.3 Harmonic Impedance in IEEE 519-1992

C. IEC 61000-3-6:2008

Information on system harmonic impedance is a prerequisite to convert emission limits from voltage to current in IEC 61000-3-6:2008. The actual assessment of harmonic impedance is a very complex problem and several measurement and calculation methods are available, but none is entirely satisfactory. Three suggested maximum impedance characteristics are introduced in the IEC standard:

(1) At low voltage, the maximum impedance is varying with the harmonic number in a straight line relationship.

(2) At 11kV, the maximum impedance curve is as shown in Figure 2.4. The harmonic impedance Z_h can be represented as the function of the fundamental system impedance X_1 and the harmonic order h: $Z_h = 2hX_1$ for $h \leq 8$, and $Z_h = hX_1$ for $h > 8$.

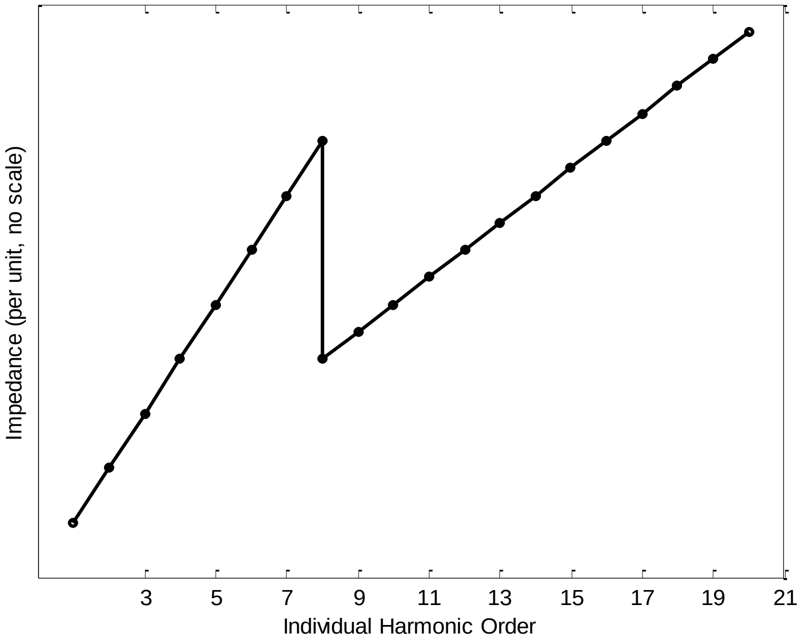

Figure 2.4 Harmonic Impedance in IEC 61000-3-6:2008

(3) At 33kV, the maximum impedance values are taken as the 1.25 times the fundamental short-circuit impedance up to 800Hz.

(4) At voltages beyond 33kV, no typical value is given.

D. Comparison

The impedance from the GB standard can be viewed as a simplification of that from IEC standard, whereas the IEEE standard defines the impedance in a totally different way. The piecewise linear function of the IEEE standard is due to the use of multiple (different) current limits combined with fixed (equal) voltage limits to provide some allowance for both load diversity and resonance. Even though the three standards are different, they all share one common impedance characteristic - the impedance increases with harmonic frequency.

Chapter 3

Interharmonic Standards

GB/T 24337-2009 [17] is the only independent power quality standard in the world focusing on the interharmonic problem. This standard contains the basics like terminology and distortion limits. It also includes limit allocation, interharmonic addition and measurements. The annexes A and B introduce the origin of the interhamonic limits, damage brought by interharmonics, and the concept of interharmonic groups. The interharmonic limit part is the emphasis of this chapter.

3.1 Background

The interharmonic distortion limit addressed in this standard is formulated based on other international standards.

A. IEC 61000-2-4:2002

This standard categories the electromagnetic environment into three classes: Class 1 for application to protected supplies for sensitive equipment with lower compatibility levels than for public networks, Class 2 for application to general power supplies with identical compatibility levels compared to public networks, and Class 3 for application to only in-plant points of coupling (IPCs) in industrial environments with higher compatibility levels for some disturbance phenomena [18].

In this standard, only the compatibility levels at frequencies close to the fundamental frequency (50 Hz or 60 Hz) are given. This is due to the beat effect on certain sensitive loads like lighting devices, which results in flicker problems. Beat frequency refers to the difference between interharmonic frequency and fundamental frequency. The relationship between beat frequency and interharmonic voltage (in percent) for a flicker level of $P_{st} = 1$ at 120V and 230V is reflected in figure 3.1. Based on this figure, a 0.2% compatibility level for interharmonic voltage is determined from flicker requirements.

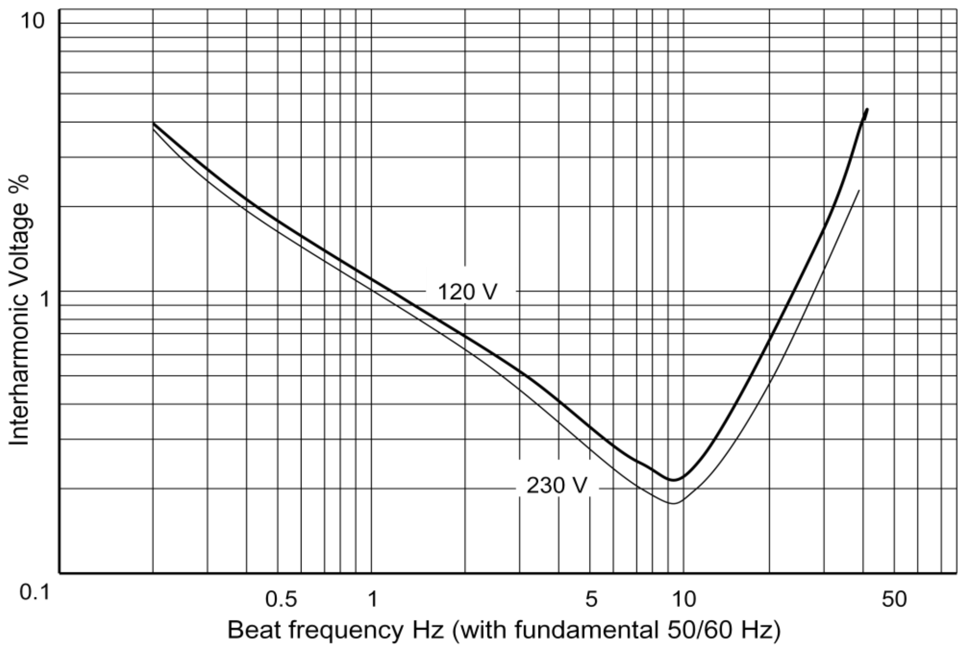

Figure 3.1 Compatibility Level for Interharmonic Voltage

B. IEC 61000-3-6:2008

Based on some examples listed in Table 3.1, a generally conservative planning level for interharmonic voltage is 0.2%. In ripple control systems, interharmonic voltages with frequencies close to the ripple control frequency and its side-band frequencies should not exist. In order to avoid mechanical resonances caused by sub-harmonic currents flowing into generators, the recommended limit could be very low. In addition to these situations, there may be other cases where the 0.2% limit is not conservative.

Equipment	Frequency (Hz)	Interharmonic voltage (%)
Incandescent/fluorescent lamps	< 100	0.2
Ripple control receivers		0.3
Television sets/ Induction rotating machines/ frequency relays	≤ 2500	0.5
Radio receivers/ Other audio equipments	$2500 < f \leq 5000$	0.3

Table 3.1 Interharmonic Limits for Equipment (IEC)

3.2 Interharmonic Limits in GB/T 24337-2009

3.2.1 General Interharmonic Limits

Although the values for interharmonic limits are still controversial and there is no agreement for interharmonic voltage distortion level limits in an international standard, GB/T 24337-2009 takes 0.2% as the limit for the voltage level below 1000 V and frequencies below 100 Hz based on the recommended planning level from IEC 61000-3-6:2008. The interharmonic voltage limit is set to be more strict for voltage levels higher than 1kV by taking into account the transfer effect from upstream system (>1kV) to downstream system (<1kV) and the more destructive influence on high voltage system equipment. Thus, the interharmonic voltage distortion value at a PCC for each individual frequency up to 800Hz should not exceed the limits shown in Table 3.2.

Individual Interharmonic Voltage (%)		
Voltage Level	Frequency, Hz	
kV	< 100	$100\sim800$
≤ 1	0.2	0.5
$1\sim220$	0.16	0.4

Table 3.2 Interharmonic Voltage Limits (GB)

3.2.2 Interharmonic Limits for Individual Customers

It is necessary to allocate properly the interharmonic voltage limits to individual end-users. The voltage addition at any individual interharmonic frequency from several disturbance sources is done using (3.1).

$$U_{ih} = \sqrt[3]{\sum_{i=1}^{k} U_{ihk}^{3}} \tag{3.1}$$

In (3.1),

ih : the interharmonic order,

k : the number of interharmonic sources, and

U_{ih} : the r.m.s. value of the interharmonic voltage of order ih from source k.

An assumption is made that only two interharmonic sources exist at one measurement point because of the relatively low number of interharmonic sources in a large scale power system. Based on the equal allocation and the summation equation (3.1), each source should be limited to $\frac{U_{ih}}{\sqrt[3]{2}} = 0.8U_{ih}$, which results in the individual customer limits listed in Table 3.3.

Individual Interharmonic Voltage (%)		
Voltage Level V	Frequency, Hz	
	< 100	$100 \sim 800$
≤ 1000	0.16	0.4
> 1000	0.13	0.32

Table 3.3 Interharmonic Voltage Limits for Individual Customer (GB)

Based on (3.1), an assessment can be made whether customer x is in compliance with the intherharmonic limits using (3.2).

$$U_{ihx} = \sqrt[3]{U_{ih*} - U_{ih0}} \tag{3.2}$$

In (3.2),

U_{ih*} : the r.m.s value of the interharmonic voltage of order ih after customer x is connected to the system and

U_{ih0} : the r.m.s value of the interharmonic voltage of order ih for the original system before customer x is connected

The calculated value U_{ihx} is compared to the appropriate value from Table 3.3 to determine compliance.

Chapter 4

Voltage Fluctuation and Flicker Standards

4.1 Introduction

4.1.1 Background

Many organizations contribute to developing the standards for managing voltage fluctuation and flicker problems. IEC establishes a comprehensive approach for voltage fluctuation and flicker including the measurement standard IEC 61000-4-15:2010 [19], limits for equipment standards IEC 61000-3-3:2013, IEC 61000-3-5:2009, and IEC 61000-3-11:2000 and the system standard IEC 61000-3-7:2008 [20]. Two standards related to the flicker phenomenon within IEEE are IEEE 519-1992 and IEEE 1453. SAC/TC1 develops the GB/T 12326-2008 standard [21] as the newest version for voltage fluctuation and flicker.

A flicker curve is a plot of amplitude of voltage fluctuation versus frequency of occurrence that corresponds to a given level of flicker severity. Individuals differ in their sensitivity to lamp flicker, thus the flicker curve defines the level for a certain percentage of observers who find it to be perceptible or objectionable. As the centerpiece in standards, two flicker curves have been used for many years. The first is the General Electric curve which is actually two curves – the borderline of visibility and borderline of irritation which was published around 1951. IEEE adopts this curve in IEEE 519-1992 and IEEE 141-1995. Another way is the flicker meter that was developed by the International Union for

Electroheat (UIE) in 1982. IEC applies this method and established IEC 868 in 1986 and IEC 868-0 in 1991 as the flicker standards. Later, IEC 61000-4-15, IEC 61000-3-7 and many other standards were developed on the basis of the flicker meter. IEEE adopts IEC Standard 61000-4-15 as IEEE Standard 1453, and IEEE 1453.1 is derived from IEC 61000-3-7:2008.

Chinese standard GB/Z 17625.5-2000 is translated from IEC 61000-3-7:1996, and GB 17625.2-2007 is identical to IEC 61000-3-3:2005 while GB/Z 17625.3-2000 is the same as IEC 61000-3-5:1994. As the recommended document for voltage fluctuation and flicker in China, GB/T 12326-2009 is also built on the basis of IEC 61000-3-7:1996. IEC 61000-3-7: 2008 is the second edition that provides guidance to determine the requirements for the connection of fluctuation installations to MV, HV and EHV public power systems. Compared to the first edition published in 1996, many revisions have been made to improve its usability which are specifically described in [22]. Therefore, a comparison will be made between GB/T 12326-2009 and IEC 61000-3-7:2008 since there exist both similarities and differences.

4.1.2 Basic concepts

GB/T 12325-2009 and IEC 61000-3-7:2008 share most concepts dealing with the voltage fluctuation and flicker problem. Three essential aspects are presented as follows:

A. Indices

The evaluation of voltage fluctuations usually considers two indices relating to a voltage quality criterion: short term flicker severity P_{st} and long term flicker severity P_{lt}, where short term is referring to a value obtained for each 10 min period and the long term refers to a 2h period. Therefore, the value of P_{lt} is typically derived from groups of 12 consecutive of P_{st} values and their relationship can summarized in (4.1).

$$P_{lt} = \sqrt[3]{\frac{1}{12} \cdot \sum_{j=1}^{12} P_{stj}^3} \tag{4.1}$$

Voltage change d and variation frequency r represent the characteristics of a voltage fluctuation. A voltage change is considered to be a change in fundamental frequency r.m.s. voltage over several cycles, and its value is determined by the difference between maximum value and minimum value as described in (4.2). The number of voltage changes within one minute is defined as r, and it can be related to frequency f as shown in (4.3).

$$d = \frac{U_{max} - U_{min}}{U_N} \times 100\% = \frac{\Delta U}{U_N} \times 100\% \tag{4.2}$$

$$f(Hz) = \frac{r(s^{-1})}{2} = \frac{r(min^{-1})}{120} \tag{4.3}$$

The IEC $P_{st} = 1$ curves for 230V and 120V applications in Figure 4.1 link the voltage change d, voltage variation frequency r and short term flicker severity P_{st} together.

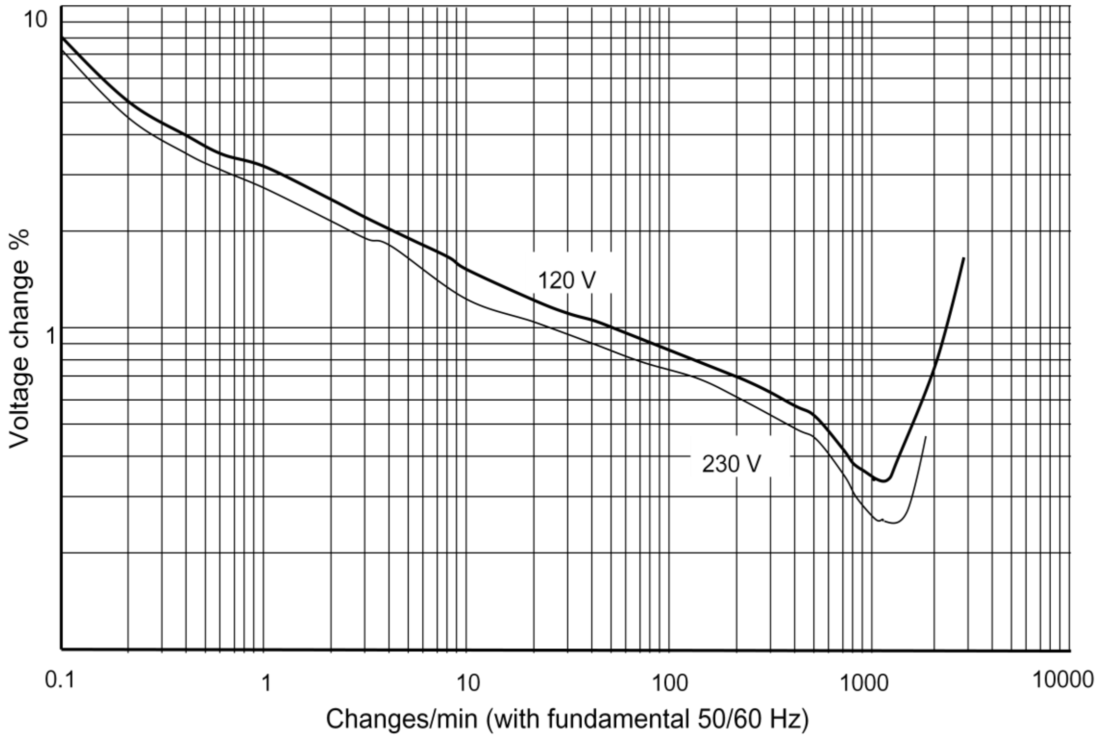

Figure 4.1 $P_{st} = 1$ Curves for 230 V and 120V Applications

B. General Principles

The proposed approach to deal with emission limit setting is dependent on end-user agreed power, the power of flicker-generating equipment and the system characteristics. Three stages quite similar to the harmonic emission limit evaluation process are given in GB and IEC flicker standards. Stage 1 offers the simplified evaluation of disturbance emission for small size customers. Stage 2 is based on an equality rule to allocate the emission limits to individual customers according to their demand with respect to the total system capacity and considering the transfer coefficient from an upstream system. Stage 3 allows higher emission levels for some special situations which should be associated with detailed evaluations.

C. Summation Law

Various fluctuating installations connected to one measurement point may present the risk of coincident voltage changes, aggregation of flicker effects and an overall increase in flicker severity. Accordingly, the summation law in equation (4.4) is used for the general combination of multiple sources for short-term flicker severity where i is the index of the sources. The same rule applies for long-term flicker severity P_{lt}.

$$P_{st} = \sqrt[\gamma]{\sum_i P_{sti}^{\gamma}} \tag{4.4}$$

The value $\gamma = 3$ has been widely accepted for most situations without additional known information. However, values of γ may change when more information is known. The value for exponent γ can change from 1 to 4 depending on the degree of the possibility of coincident voltage changes. Lower values are generally used when greater coincidence is expected.

4.2 Comparison

4.2.1 Flicker Severity

A. Flicker Severity

Flicker severity is the centerpiece of the entire voltage fluctuation and flicker standard structure. Different limits for flicker severity are provided in GB/T 12326-2009 and IEC 61000-3-7:2008.

IEC 61000-3-7:2008 develops a complete system for the electromagnetic environment and introduces some basic EMC concepts like compatibility level, planning level and emission level in the same way previously discussed for harmonics. GB/T 12326-2009 does not establish a total EMC management approach but only offers flicker severity limits which are functionally equal to the planning levels in the IEC standard. The "limit" concept in the GB standard represents the overall flicker level of the system which corresponds to the planning level described in the IEC standard. What is more, despite the mention of both P_{st} and P_{lt} in the GB standard, only P_{lt} is adopted as a criterion as shown in Table 4.1. P_{st} is regarded only as an element for P_{lt} calculations. Indicative values of planning levels for both P_{st} and P_{lt} are given in Table 4.2 taken from the IEC standard. Therefore, a direct comparison will only consider the limits for long-term flicker severity P_{lt}.

Long-term Flicker Severity	$\leq 110\text{kV}$	$> 110kV$
P_{lt}	1	0.8

Table 4.1 Flicker Severity P_{lt} Limits (GB)

	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

Table 4.2 Planning Levels for P_{st} and P_{lt} (IEC)

From the values given in Tables 4.1 and 4.2, it can be concluded that the IEC standard specifies more strict limits for P_{lt} in MV, HV and EHV systems.

B. Severity Indicators

To solve the complexity brought by the exponential summation law, severity indicators A_{st} and A_{lt} sometimes replace the original P_{st} and P_{lt} indices by setting the relationships $A_{st} = P_{st}^{\gamma}$ and $A_{lt} = P_{lt}^{\gamma}$ in the annex of IEC 61000-3-7:2008. Thus, the corresponding planning levels for A_{st} and A_{lt} are transformed to the values in Table 4.3. This concept is not mentioned in GB/T 12326-2009.

	MV	HV-EHV
A_{st}	0.73	0.5
A_{lt}	0.3	0.2

Table 4.3 Planning Levels for A_{st} and A_{lt} (IEC)

4.2.2 Voltage Changes

A. Rapid Voltage Changes

Similar to flicker severity, the limits for voltage changes in Table 4.4 from GB/T 12326-2009 should be compared to the indicative planning levels in Table 4.5 offered by IEC 61000-3-7:2008, since the GB standard does not establish the whole EMC management approach. Note that rapid voltage changes are also not included in the normal overall EMC management approach used by IEC.

	Number of changes per hour r	$d\%$	
		LV, MV	HV
Periodic voltage changes	$r \leq 1$	4	3
	$1 < r \leq 10$	3	2.5
	$10 < r \leq 100$	2	1.5
	$100 < r \leq 1000$	1.25	1
Aperiodic voltage changes		3	2.5

Table 4.4 Limits for Rapid Voltage Changes (GB)

The limits values provided in Table 4.4 cover the voltage level in LV, MV and HV system but without any for EHV systems compared to the planning level values in Table 4.5 from IEC. Table 4.4 from the GB standard offers more information on the limits for voltage changes at higher frequencies.

Number of changes n	$\Delta U/U_N\,\%$	
	MV	HV/EHV
$n \leq 4$ per day	5-6	3-5
$n \leq 2$ per hour and $n > 4$ per day	4	3
$2 < n \leq 10$ per hour	3	2.5

Table 4.5 Indicative Planning Levels for Rapid Voltage Changes (IEC)

B. Relative Voltage Change

Simplified calculation of the relative voltage change d(GB) and ΔV(IEC) is described in GB/T 12326-2009 and IEC 61000-3-7:2008. Both standards give the equations for the following three situations and the GB standard presents one additional special case formula for arc furnaces:

1) Balanced three-phase loads when given the resistance R_L, the reactance X_L, the rated voltage U_N, the active power change $\Delta \mathrm{P_i}$ and the reactive power change ΔQ_i for load i:

$$d = \frac{R_L \cdot \Delta P_i + X_L \cdot \Delta Q_i}{U_N^2} \times 100\% \tag{4.5}$$

2) Balanced three-phase loads when the reactive power change $\Delta \mathrm{Q_i}$ is the dominant part, where ΔS_i represents the load power change and S_{sc} represents the short-circuit power:

$$d = \frac{\Delta S_i}{S_{sc}} \times 100\% \tag{4.6}$$

3) Two-phase load, where ΔS_i represents the load power change and S_{sc} represents the short-circuit power:

$$d = \frac{\sqrt{3} \cdot \Delta S_i}{S_{sc}} \times 100\% \tag{4.7}$$

The special case of the arc furnace is emphasized in GB/T 12326-2009. Voltage fluctuation and flicker may occur due to the large amount of random reactive power drawn especially during the melting period of the furnace. The maximum voltage fluctuation d_{max} caused by the arc furnace at the PCC can be calculated using (4.8), where ΔQ_{max} is the maximum reactive power change. The long term flicker severity as a function of d_{max} is expressed in (4.9).

$$d_{max} = \frac{\Delta Q_{max}}{S_{sc}} \times 100\% \tag{4.8}$$

$$P_{lt} = K \cdot d_{max} \tag{4.9}$$

In (4.9),

K : the factor considering the diversity of the arc furnace and the value is taken from the following:

$K_{lt} = 0.48$ for an a.c. arc furnace,

$K_t = 0.38$ for an d.c. arc furnace, or

$K_1 = 0.28$ for a refining arc furnace.

4.2.3 General Principles

A. Coordination

Coordination is a core principle in IEC 61000-3-7:2008 and the same approach is used for harmonics, flicker and unbalance. The three defined EMC targets are developed around this philosophy. Representing a 95% probability level over the entire system, the compatibility levels work as the reference values for coordinating the emission and immunity of equipment in order to ensure EMC in the whole system. Planning levels are generally chosen to allow the coordination of voltage fluctuations between different voltage levels. Only indicative planning levels are given and they can be modified by the system operator or owner for use as their specific internal quality objectives. Emission limits are derived from planning levels so that they follow the coordination approach.

GB/T 12326-2009 provides the system-level values for long term flicker severity which could be apportioned to individual customers as emission limits. Therefore, it also follows the coordination process except that this “system value” cannot be modified in theory. In order to meet the requirement, if the allocation process fails to result in meeting the required system-level value, system owner will take actions to fix the problem to achieve the power quality goal.

B. Stage 1

The simplified evaluation criteria are illustrated in Table 4.6 from both GB/T 12326-2009 and IEC 61000-3-7:2008. The criteria for automatic connection without further study for fluctuating loads can be expressed by the ratio of apparent power variations ΔS to the system short circuit power S_{sc} and a repetition rate r.

r min^{-1}	$K = (\Delta S/S_{sc})_{max}$ %
$r > 200$	0.1
$10 \leq r \leq 200$	0.2
$r < 10$	0.4

Table 4.6 Stage 1 Limits

In addition to the criteria of Table 4.6, GB/T 12326-2009 includes two more criteria that, if satisfied, eliminate the need for further evaluation:

a) HV customers with $(\Delta S/S_{sc})_{max} < 1\%$ and

b) Individual fluctuating installations with $P_{lt} < 0.25$.

C. Stage 2

(1) Global emission

The concept of sharing global contributions has already been introduced in the harmonic chapter as expressed in (2.7) and Figure 4.2. The method of calculating the flicker transfer coefficient in (2.7) for global emission allocation is described in both GB and IEC standards. The flicker transfer coefficient between two points A and B shown in Figure 4.2 where the dominant flicker source is located at point B can be calculated by (4.10).

$$T_{PstBA} = P_{stA}/P_{stB} \tag{4.10}$$

Compared to the IEC standard, the GB standard adds one more equation (4.11) to also determine the transfer coefficient in terms of short-circuit capacity.

$$T_{PstBA} = \frac{S'_{scA}}{S_{scA} - S'_{scB}} \tag{4.11}$$

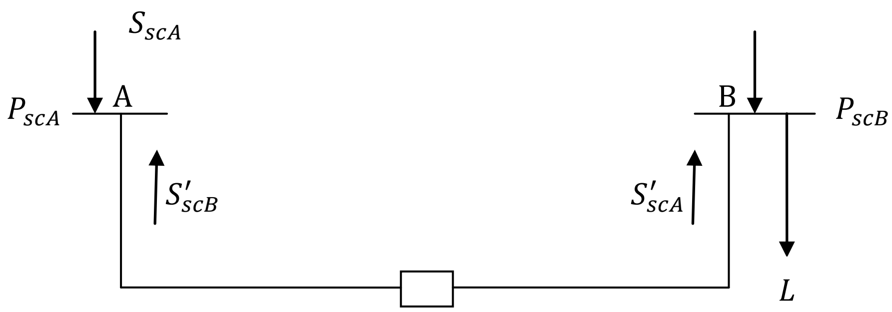

Figure 4.2 Flicker Transfer in System A and B

In (4.10) and (4.11),

P_{stA} : the short-term flicker severity at point A due to the flicker source at point B,

P_{stB} : the short-term flicker severity at point B,

S_{scA} : the short-circuit capacity at point A,

S'_{scA} : the short-circuit contribution from A to B when the short circuit happens at point B, and

S'_{scB} : the short-circuit contribution from B to A when the short circuit happens at point A.

(2) Individual emission limits

A fraction of the global emission level G_{Plt} will be apportioned to individual customers considering the ratio between the agreed power S_i and the total supply capacity S_t of the MV or HV system. Differences appear in the equation for calculating the individual emission limit E_{Plti} allocated from the global emission level G_{Plt} in GB/T 12326-2009 and IEC 61000-3-7:2008. Taking the MV system as the example, (4.12) shows the principle in the GB standard while (4.13) is from the IEC standard.

$$E_{Plti} = G_{PltMV}\sqrt[3]{\frac{S_i}{S_t}\cdot\frac{1}{F}} \tag{4.12}$$

In (4.12),

F ： the coincident factor for voltage fluctuating installations, the typical value is between 0.2 and 0.3.

$$E_{Plti} = G_{PltMV}\sqrt[\gamma]{\frac{S_i}{(S_t - S_{LV})}} \tag{4.13}$$

In (4.13),

S_{LV} ： the total power of installations supplied directly at LV and

γ ： the summation law exponent discussed in 4.1.

The equation from the GB standard takes account of the diversity of flicker sources by using the factor F, while the IEC standard specifies that the total supply capacity S_t should subtract the value of total power S_{LV} from LV installations when calculating the individual emission limits in MV systems. The value used for the ratio calculation in HV systems will be S_t.

Considering calculations sometimes result in impractical limits for end-users with low agreed power, minimum emission limits at MV and HV-EHV system are also provided as shown in Table 4.7 for this special circumstance in IEC 61000-3-7:2008.

E_{Psti}	0.35
E_{Plti}	0.25

Table 4.7 Minimum Emission Limits (IEC)

D. Stage 3

The acceptance of higher emission levels on a conditional basis is described in detail in the IEC standard while there is little guidance on applying stage 3 in the GB standard. The IEC standard discusses the factors that may leave a margin on the system for allowing higher emission limits and the application of temporary stage 3 limits. Also, the factor F related to the load diversity which is not used in stage 2 can be included in stage 3.

4.2.4 Shape Factor Curves

Considering the rare probability for sinusoidal, triangular or other wave shape changes, GB/T 12326-2009 offers the $P_{st} = 1$ curves in Figure 4.1 only for 230V for periodic step voltage changes with square shape. However in practice, most voltage changes may not be stepwise in nature and shape changes like sinusoidal, triangular, ramp and other common shapes have been considered. Accordingly, IEC 61000-3-7:2008 provides (4.14) to predict P_{st} for other wave shape voltage changes by introducing a new element – the shape factor value F_s. The value for F_s is taken from one of several curves given in various IEC standards. Shape factors are not included in the GB standard.

$$P_{st} = (\frac{d}{d_{P_{st}=1}}) * F_s \quad (4.14)$$

In (4.14),

d : the actual relative voltage change and

$d_{P_{st}=1}$: the required value of relative voltage change to produce $P_{st} = 1$ for a given frequency as read from Figure 4.1.

Chapter 5

Conclusions

Analysis and comparison of Chinese and international standards on harmonics, interharmonics and voltage fluctuations and flicker have been presented in this thesis. By introducing the basic content of GB/T 14549-93, IEEE 519-1992 and IEC 61000-3-6:2008, comparisons have been presented for five separate areas of harmonic standardization: application, driving principle, harmonic voltage limits, harmonic current limits and impedance. Despite the many differences presenting during the comparisons, there is no doubt that all three standards fit very well and are capable of maximizing voltage quality over entire supply systems.

Chinese standard GB/T 24337-2009 is the only independent standard specifically addressing the interharmonic problem. This standard is based on other international standards like IEC 61000-2-4:2002 and IEC 61000-3-6:2008, as well as the specific situation in China. Analyzing the emission limits provided in the GB interharmonic standard without any comparison was the only thing possible in this research.

IEC 61000-3-7:2008 is one of the most widely accepted voltage fluctuation and flicker standards in industry. Chinese standard GB/T 12326-2009 is formulated on this IEC standard. The differences between IEC 61000-3-7:2008 and GB/T 12326-2009 were evaluated on the aspects of flicker severity, voltage change, driving principle and shape factor curves.

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