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IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

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USA

IEEE Std 1453™-2015
(Revision of
IEEE Std 1453-2011)

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Approved 3 September 2015

IEEE-SA Standards Board

Abstract: Background on light flicker caused by fluctuations in power demands of variable loads is presented in this recommended practice. A flicker measurement method is presented using a meter that is completely described in IEC 61000-4-15. The short-term (P_{st}) and long-term (P_{lt}) flicker indices used for the analysis of flicker data are defined. Flicker limits for various voltage levels are presented. An assessment procedure for evaluating flicker compliance against emission limits is described. Methodologies to analyze background flicker to identify the flicker contribution of single loads are also presented.
Keywords: flicker, fluctuating loads, IEEE 1453™, power systems

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3 Park Avenue, New York, NY 10016-5997, USA

PDF: ISBN 978-0-7381-9844-6 STD20321
Print: ISBN 978-0-7381-9845-3 STDPD20321

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Introduction

This introduction is not part of IEEE Std 1453-2015, IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems.

Voltage fluctuations on electric power systems sometimes give rise to noticeable illumination changes from lighting equipment. The frequency of these voltage fluctuations is much less than the 50 Hz or 60 Hz supply frequency. However, they may occur with enough frequency and magnitude to cause irritation for people observing the illumination changes. This phenomenon is often referred to as flicker, lamp flicker, and sometimes voltage flicker. Often times, the terms have been used interchangeably. IEEE Std 141™-1993 [B14] and IEEE Std 519™-1992 [B15] contain charts showing allowable voltage fluctuations. The advent of high-power electronic utilization equipment and mitigation equipment has given rise to some very complex voltage fluctuations that are not easily handled by IEEE Std 141-1993 [B14] and IEEE Std 519-1992 [B15]. For this reason, the IEEE has worked in close cooperation with the International Union for Electroheat (UIE) and the International Electrotechnical Commission (IEC) to enhance existing standards to include a broader part of the world community. In 2004, IEEE Std 1453-2004 was published, adopting the IEC flickermeter standard and providing recommended levels. IEEE Std 1453-2011 adopted the 2010 edition of the IEC 61000-4-15, moving the recommended acceptable flicker levels to its annex, facilitating the adoption of the IEC/TR 61000-3-7 in IEEE Std 1453.1™-2012. This present version of IEEE Std 1453 replaces both IEEE Std 1453-2011 and IEEE Std 1453.1-2012. This edition uses the IEC flicker methodology while providing additional information.

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IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems

1. Overview

1.1 Scope

This recommended practice provides background on light flicker caused by fluctuations in power demands of variable loads. A flicker measurement method is presented using a meter that is completely described in IEC 61000-4-15. The short-term (P_{st}) and long-term (P_{lt}) flicker indices used for the analysis of flicker data are defined. Flicker limits for various voltage levels are presented. An assessment procedure for evaluating flicker compliance against emission limits is described. Methodologies to analyze background flicker to identify the flicker contribution of single loads are also presented.

The document provides ways to estimate flicker levels at the Point of Common Coupling (PCC) depending on the type of the load. This document includes example terms and language that can be the basis for defining relative responsibilities and assessment methods for customer installations that may cause flicker.

1.2 Purpose

The purpose of this document is to provide guidance to system operators, owners, and engineers who are responsible for providing electrical service to installations that cause voltage fluctuations. It provides guidance on the principles and methodology that can be used to determine requirements for connecting fluctuating loads to both radial and network systems. Methods for determining appropriate flicker planning

levels and emission limits for fluctuating loads as well as those that create rapid voltage changes are provided.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 61000-4-15, Electromagnetic compatibility (EMC)—Part 4-15: Testing and measurement techniques—Flickermeter—Functional and design specifications.[1]

IEC 61000-3-7, Electromagnetic compatibility (EMC)—Limits—Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[2]

customer: A person, company, or organization that operates an installation connected to, or entitled to be connected to, a supply system by a system operator or owner.

disturbance level: The magnitude of an electromagnetic disturbance measured and evaluated in a specified way.

electromagnetic compatibility (EMC): The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances in that environment.

NOTE 1—Electromagnetic compatibility is a condition of the electromagnetic environment such that, for every phenomenon, the disturbance emission level is sufficiently low and immunity levels are sufficiently high so that all devices, equipment and systems operate as intended.[3]

NOTE 2—Electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that the immunity levels of the devices, equipment and systems at any location are not exceeded by the disturbance level at that location resulting from the cumulative emissions of all sources and other factors such as circuit impedances. Conventionally, compatibility is said to exist if the probability of the departure from intended performance is sufficiently low. See Clause 4 of IEC 61000-2-1.

NOTE 3—Where the context requires it, electromagnetic compatibility may be understood to refer to a single disturbance or class of disturbances.

NOTE 4—Electromagnetic compatibility is a term used also to describe the field of study of the adverse electromagnetic effects that devices, equipment, and systems undergo from each other or from electromagnetic phenomena.

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[1] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http:// www.ansi.org/).

[2] *IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

[3] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

(electromagnetic) compatibility level: The specified electromagnetic disturbance level used as a reference level in a specified environment for coordination in the setting of emission and immunity limits.

NOTE—By convention, the compatibility level is chosen so that there is only a small probability (for example 5%) that it will be exceeded by the actual disturbance level.

electromagnetic disturbance: Any electromagnetic phenomenon that may degrade the performance of a device, equipment, or system, or adversely affect living or inert matter.

emission: The phenomenon by which electromagnetic energy emanates from a source of electromagnetic disturbance.

NOTE—For the purpose of this document, emission refers to phenomena or conducted electromagnetic disturbances that can cause flicker or fluctuations of the supply voltage.

emission level (of a disturbing source): The level of a specified electromagnetic disturbance type emitted from a particular device, equipment or system.

emission limit: The maximum emission level specified for a particular device, equipment, system, or disturbing installation as a whole.

flicker: The subjective impression of fluctuating luminance caused by voltage fluctuations.

NOTE—Above a certain threshold, flicker becomes annoying. The annoyance grows very rapidly with the amplitude of the fluctuation. At certain repetition rates even very small amplitudes can be annoying.

flicker severity: The intensity of flicker annoyance defined by the UIE IEC flicker measuring method and evaluated by the following quantities:

— Short-term severity (P_{st}) measured over a period of ten minutes
— Long-term severity (P_{lt}) calculated from a sequence of 12 consecutive P_{st} values (i.e., over a two hour interval)

fluctuating installation: An electrical installation as a whole (i.e., including fluctuating and non-fluctuating parts) that is characterized by repeated or sudden power fluctuations, or start-up or inrush currents that can produce voltage fluctuations or rapid voltage changes on the supply system to which it is connected.

NOTE—For the purpose of this document, all references to fluctuating installations not only include loads, but also generating plants.

fundamental frequency: The frequency in the spectrum obtained from a Fourier transform of a time function to which all the frequencies of the spectrum are referred.

NOTE 1—For the purpose of this document, the fundamental frequency is the same as the power supply frequency (definition 3.12 in IEC 61000-3-7).

NOTE 2—In the case of a periodic function, the fundamental frequency is generally equal to the frequency of the function itself.

generating plant: Any equipment that is a source of electric power together with any directly connected or associated equipment such as a unit transformer or converter.

immunity (to a disturbance): The ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.

immunity level: The maximum level of a given electromagnetic disturbance on a particular device, equipment or system for which it remains capable of operating with a declared degree of performance.

interharmonic frequency: Any frequency that is not an integer multiple of the fundamental frequency.

NOTE 1—By extension from harmonic order, the interharmonic order is the ratio of the interharmonic frequency to the fundamental frequency. This ratio is not an integer (recommended notation "m").

NOTE 2—In the case where m < 1 the term subharmonic frequency may be used.

interharmonic component: A component that has an interharmonic frequency. For brevity, such a component may be referred to simply as an "interharmonic".

interharmonic voltage: A sinusoidal voltage with a frequency not equal to an integer multiple of the fundamental.

normal operating conditions: The operating conditions of the system or of the disturbing installation typically including all generation variations, load variations, and reactive compensation or filter states (e.g., shunt capacitor states), planned outages and arrangements during maintenance and construction work, non-ideal operating conditions and normal contingencies under which the considered system or disturbing installation has been designed to operate.

NOTE—Normal system operating conditions typically exclude: conditions arising as a result of a fault or a combination of faults beyond that planned for under the system security standard, exceptional situations and unavoidable circumstances (for example: force majeure, exceptional weather conditions and other natural disasters, acts by public authorities, industrial actions), cases where system users significantly exceed their emission limits or do not comply with the connection requirements, and temporary generation or supply arrangements adopted to maintain supply to customers during maintenance or construction work, where otherwise supply would be interrupted.

$\boldsymbol{P_{inst}}$**:** The instantaneous flicker sensation.

$\boldsymbol{P_{inst,max}}$**:** The peak value of the instantaneous flicker sensation P_{inst} measured during the observation period.

$\boldsymbol{P_{lt}}$**:** The long-term flicker severity

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{i=1}^{12} P_{st_i}^3}$$

where

(i = 1, 2, 3, ...) are consecutive readings of the short-term severity P_{st}

$\boldsymbol{P_{st}}$**:** The short-term flicker severity. If not specified differently, the P_{st} evaluation time is 10 minutes. For the purpose of power quality surveys and studies, other time intervals may be used, and have to be defined in the index. For example a 1 minute interval should be written as $P_{st,1m}$.

NOTE—See Equation (1) and related discussion.

planning level: The level of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions from the installations in a particular system, in order to coordinate those limits with all the limits adopted for equipment and installations intended to be connected to the power supply system.

NOTE—Planning levels are considered internal quality objectives to be specified at a local level by those responsible for planning and operating the power supply system in the relevant area.

point of common coupling (PCC): The point in the public system that is electrically closest to the installation concerned and to which other installations are or may be connected. The PCC is a point located upstream of the considered installation.

NOTE—A supply system is considered as being public in relation to its use, and not its ownership.

point of connection (POC): The point on a public power supply system where the installation under consideration is, or can be, connected.

NOTE—A supply system is considered as being public in relation to its use, and not its ownership.

point of evaluation (POE): The point on a public power supply system where the emission levels of a given installation are to be assessed against the emission limits. This point can be the point of common coupling (PCC) or the point of connection (POC) or any other point specified by the system operator or owner or agreed upon.

NOTE—A supply system is considered as being public in relation to its use, and not its ownership.

rapid voltage changes (RVC): Changes in fundamental frequency rms voltages over several cycles; rapid voltage changes could also be in the form of cyclic changes .

NOTE—Rapid voltage changes are often caused by start-ups, inrush currents, or switching operation of equipment.

rms voltage refreshed each half-cycle, Vrms(½): Value of the rms voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle (definition 3.22 in IEC 61000-4-30).

NOTE 1—This technique is independent for each channel and will produce rms values at successive times on different channels for polyphase systems.

NOTE 2—This value is used only for voltage dip, voltage swell, interruption, and RVC detection and evaluation, in Class A.

NOTE 3—This rms voltage value may be a phase-to-phase value or a phase-to-neutral value.

short-circuit power: The theoretical value expressed in MVA of the initial symmetrical three-phase short-circuit power at a point on the supply system. It is defined as the product of the initial symmetrical short-circuit current, the nominal system voltage, and the factor √3 with the aperiodic component (dc) being neglected.

supply system: All the lines, switchgear, and transformers operating at various voltages that make up the transmission systems and distribution systems to which customers' installations are connected.

system operator or owner: The entity responsible for making technical connection agreements with customers who are seeking connection of load or generation to a distribution or transmission system.

***T_{long}*:** The long-term time interval for the P_{lt} evaluation, which is always an integer multiple of the short term flicker severity evaluation P_{st}. If not specified differently the long-term interval T_{long} is 12 × 10 minutes, i.e., 2 hours. For the purpose of power quality surveys and studies, other time intervals may be used.

***T_{short}*:** The short-term time interval for the P_{st} evaluation. If not specified differently, the short-term interval T_{short} is 10 minutes.

transfer coefficient (influence coefficient): The relative level of disturbance that can be transferred between two busbars or two parts of a power system for various operating conditions.

voltage fluctuations: A series of voltage changes or a cyclic variation of the voltage envelope.

4. History

Variation in light output from an incandescent lamp due to changes in the applied voltage may have been experienced as far back as 1801 when Sir Humphry Davy passed current through a platinum strip, producing light. Since that time the incandescent lamp has undergone many changes in filament design and housing techniques, leading to its commercialization by the 1880s. Early dc lighting systems were often powered by generators installed within the building and were not subjected to voltage fluctuations by other loads. By 1895 the world's first large-scale generating plant at Niagara Falls was operational, later sending ac power to factories and cities up to 20 miles away in Buffalo (Gawronski, et al. [B8]). From that point forward the electrification of North America grew rapidly, with homes and factories now being supplied from electrical distribution systems, giving rise to the modern problem of light flicker. Studies, including those by H.E. Ives in 1909 [B21] and Dr. Irving Langmuir in 1914 [B28], concluded that flicker was a complex phenomenon resulting from the magnitude of the fluctuation, frequency and physiological or psychological factors.

In 1925 General Electric published a perceptibility curve developed from a collection of flicker studies that would later be known as the GE flicker curve. A 1937 report prepared by Utilities Coordinated Research, Inc. [B39] published the flicker curves used by several utilities that demonstrated a wide range of recommended limits, the result of varying individual sensitivity. More important, this report provided the definitions of cyclic flicker as the result of periodic fluctuations and noncyclic flicker as the result of occasional fluctuations.

The GE flicker curve, the most widely adopted flicker curve in the industry, is a composite of many of the studies from the 1930s (Walker [B46]) and was published by General Electric in its Distribution Data Book GET-1008L. Beginning in 1976, IEEE Std 141-1993 [B16] included the GE flicker curve, while the earlier 1969 version contained a curve from Consolidated Edison Company. Similar adoption of the GE flicker curve took place in the second revision of IEEE Std 519™-1992 [B17] and the curve itself is shown in Figure 1. One curve represents the borderline where most people began to perceive light flicker and another curve represents the borderline of irritation. The curves show maximum sensitivity to flicker at 7−8 fluctuations per second. The curves were developed based on standard rectangular modulations of the 60-Hz sine wave. Such curves are suitable for step changes in RMS voltages, but are not suitable for predicting flicker caused by other sources like arc furnaces, which are random in nature and have irregular wave shapes. Additional drawbacks of these curves include the unsuitability to handle complex voltage modulation due to use of adaptive var compensation for flicker control of seam welders and the inability to address multiple dosage issues (Halpin [B10]). Despite these drawbacks, these curves are still used by many electric utilities today as a tool for imposing flicker limits on industrial customers connected to the grid.

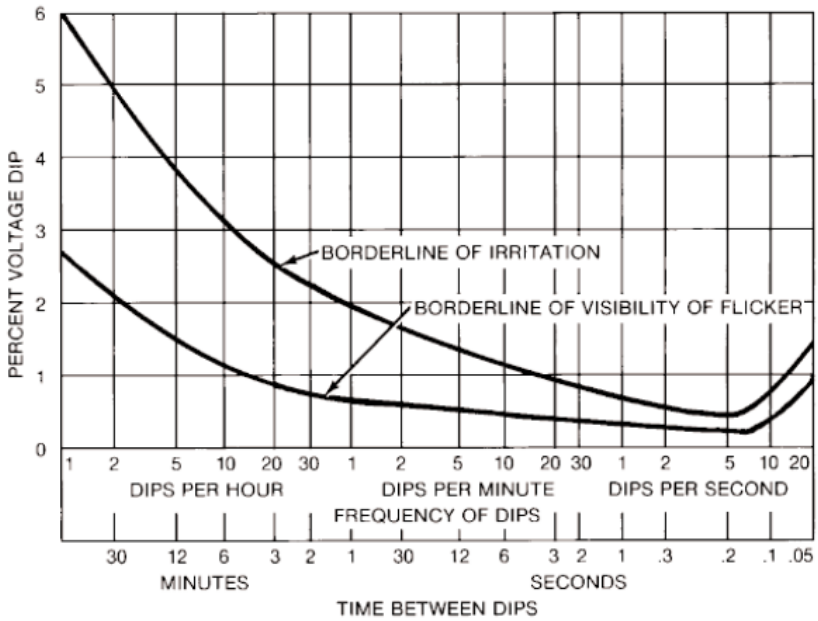


Figure 1—GE flicker curve [B14]

In Europe, studies of the lamp-eye-brain response were performed as early as 1917 by K. Simons [B38] who recognized complexities of the human response to flicker. Later works by H. de Lange [B25], [B26] and C. Rashbass [B34] were used in the development of the UIE/IEC Flickermeter during the 1970s. In 1986 IEC-868 was published, providing the design specifications for a universal flickermeter to replace several national flickermeters that were already in use (Cai, [B3]). IEC 61000-4-15 was published in 1992; however, only the 230 V, 50 Hz incandescent lamps were covered. The IEEE worked closely with UIE and IEC to expand coverage to the 120 V, 60 Hz lamp, resulting in an internationally accepted standard in 2003. In 2004, IEEE Std 1453 was published, adopting the flickermeter standard and providing recommended levels. The 2011 publication adopted the 2010 edition of IEC 61000-4-15, moving the recommended acceptable flicker levels to its annex, facilitating the adoption of IEC 61000-3-7 in IEEE Std 1453.1. This technical report published by the IEC provided guidance on the connection of fluctuating loads to utility systems.

5. Recommendations for characterizing flicker levels

5.1 Introduction to flicker

Fluctuations in system voltage can result in observable changes in the light output of electric lamps and is mostly a problem when it is observed by the human eye and is severe enough to be perceived as flicker. It can be an annoyance and hindrance to workplace productivity and affect visually induced worker discomfort.

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by ANSI C84.1 [B1]. A plot of the RMS voltage magnitude vs. time such as that in Figure 2 can be used to illustrate the variations. The characteristic shown is due to the randomly changing arc characteristic as scrap steel is melted in an electric arc furnace (EAF).

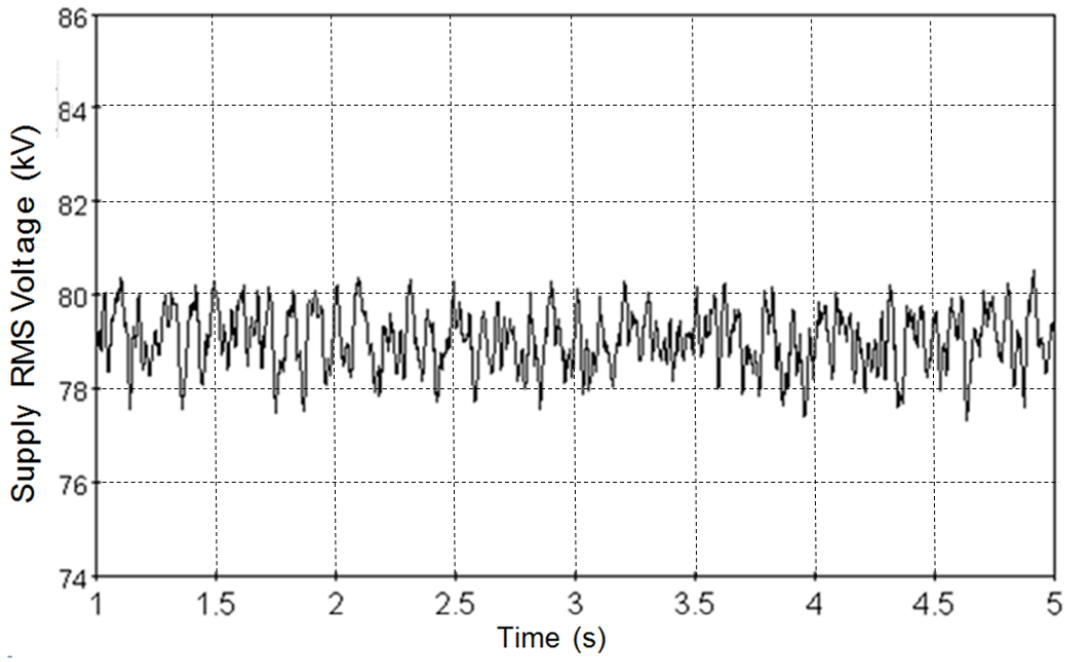


Figure 2—Example of voltage fluctuations caused by an EAF operation

5.2 IEEE 1453 flicker monitoring procedures

Flicker monitoring has been standardized over most of the world using a meter that is completely described in IEC 61000-4-15. This measurement method is based on many years of combined research by engineers and scientists in the areas of the human ocular system, brain reaction, and lamp response. Figure 3 is a block diagram of the flicker meter. The short description of individual blocks is given after the figure.

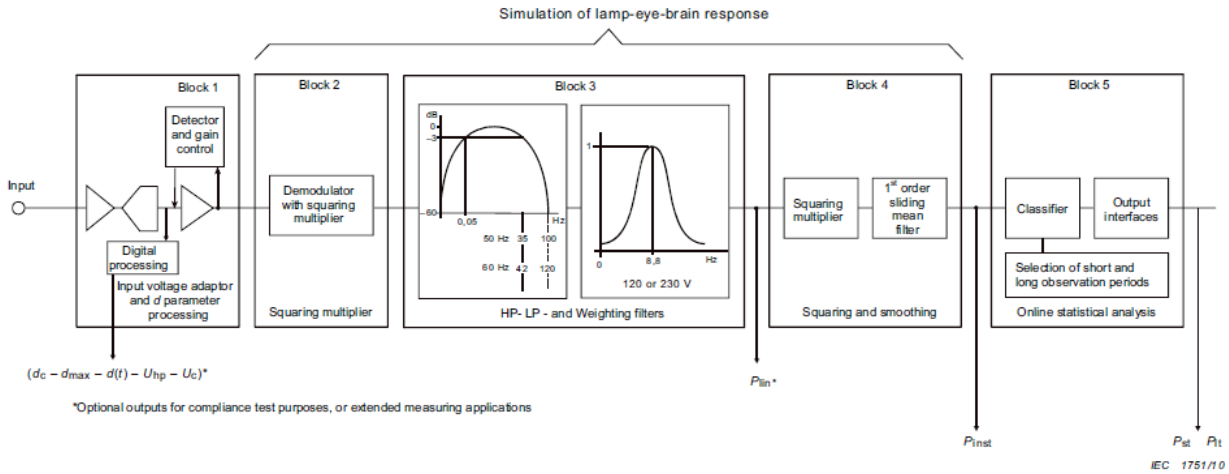


Figure 3—Functional block diagram for the IEC flickermeter

Block 1 is an input voltage adapter that scales the input half-cycle RMS value to an internal reference level. This allows flicker measurements to be made based upon a percent ratio rather than dependent upon the input carrier voltage level.

Block 2 is simply a squaring demodulator that squares the input to separate the low frequency (0.5−30 Hz) voltage fluctuation (modulating signal) from the main voltage signal (carrier signal), thus simulating the behavior of the incandescent lamp.

Block 3 consists of multiple filters that serve to filter out unwanted frequencies produced by the demodulator and also to weight the input signal according to the incandescent lamp eye-brain response. The lamp eye-brain response is represented with a 4th order bandpass filter, also known as the weighting filter. This filter has the purpose of weighting the input based upon the particular characteristics of the lamp.

Block 4 consists of a squaring multiplier and sliding mean filter. The input voltage signal is squared to simulate the non-linear eye-brain response, while the sliding mean filter averages the signal to simulate the short-term storage effect of the brain. The output of this block is considered to be the instantaneous flicker level. A level of unity on the output of this block corresponds to perceptible flicker.

The output of the Block 4 of the flickermeter is statistically processed in Block 5. The output is divided into suitable classes, thus creating a histogram. A PDF (probability density function) is created based upon each class and from this a CDF (cumulative distribution function) can be formed. The CDF can be thought of as the probability that the instantaneous flicker sensation will not exceed a certain level. Figure 4 gives a graphical demonstration of both the probability density and cumulative distribution functions for 64 classes.

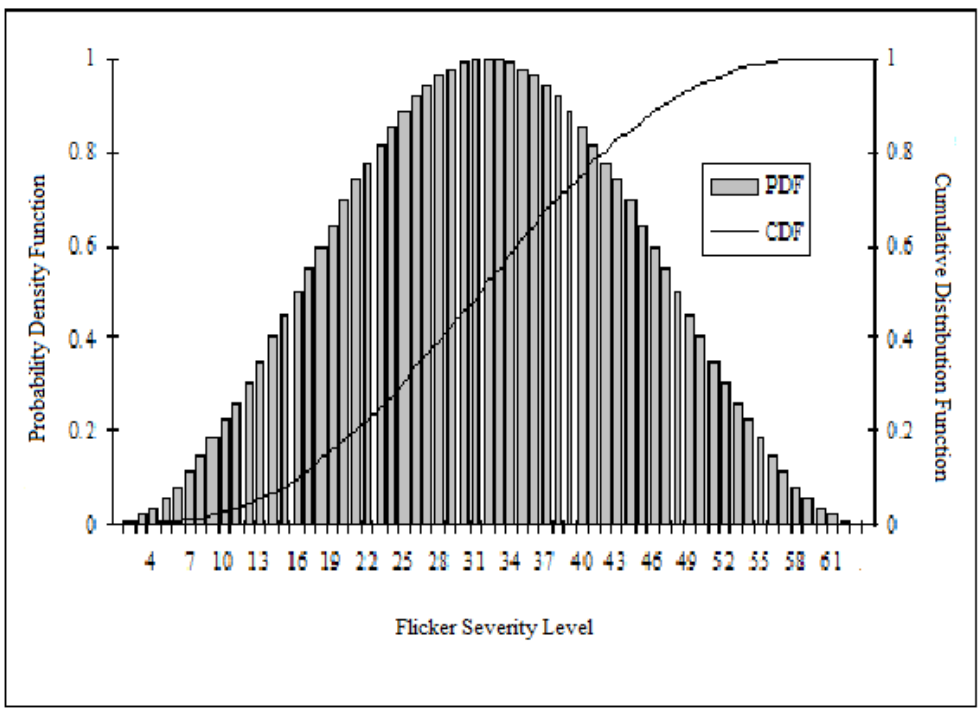


Figure 4—Cumulative distribution and probability density curves

Flicker level evaluation can be divided into two categories, short-term and long-term. Short-term evaluation of flicker severity, P_{st}, is based upon an observation period of 10 min. This period is based upon assessing disturbances with a short duty-cycle or those that produce continuous fluctuations. P_{st} can be found using Equation (1).

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \tag{1}$$

where, the percentages $P_{0.1}$, P_{1s}, P_{3s}, P_{10s} and P_{50s} are the flicker levels that are exceeded 0.1, 1.0, 3.0, 10.0, and 50.0 percent of the time. These values are taken from the cumulative distribution curve (CDF) discussed previously. The suffix *s* represents the smoothed value obtained using Equation (2) through Equation (5). It may be noted that "*P*" terms on the right side of these equations represent the flicker levels that are exceeded a percent of the time specified as sub-script. For example, $P_{0.7}$ in Equation (2) represents the flicker level that is exceeded 0.7% of the time.

$$P_{1s} = \frac{P_{0.7} + P_1 + P_{1.5}}{3} \tag{2}$$

$$P_{3s} = \frac{P_{2.2} + P_3 + P_4}{3} \tag{3}$$

$$P_{10s} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \tag{4}$$

$$P_{50s} = \frac{P_{30} + P_{50} + P_{80}}{3} \tag{5}$$

The long term flicker severity, P_{lt}, is calculated from 12 successive P_{st} values using Equation (6). In Equation (6) a cubic summation of flicker sensation was considered. Cubic summation is applicable where the risk of coincident voltage changes is small and the majority of cases fall under this category.

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} P_{st\,j}^{3}} \tag{6}$$

The original IEC standard (IEC 61000-4-15) was based on the effects of voltage fluctuations on a 60 W incandescent light on 230 V systems. A 60 W incandescent light bulb designed for 120 V is not as sensitive to the same voltage fluctuations as a 60 W, 230 V lamp because the filament is thicker (longer thermal time constant) to handle the higher current levels associated with the same power rating. As a result, an additional weighting curve was developed for 120 V applications, which are more common in North America. The 120 V and 230 V weighting curves are compared in Figure 5.

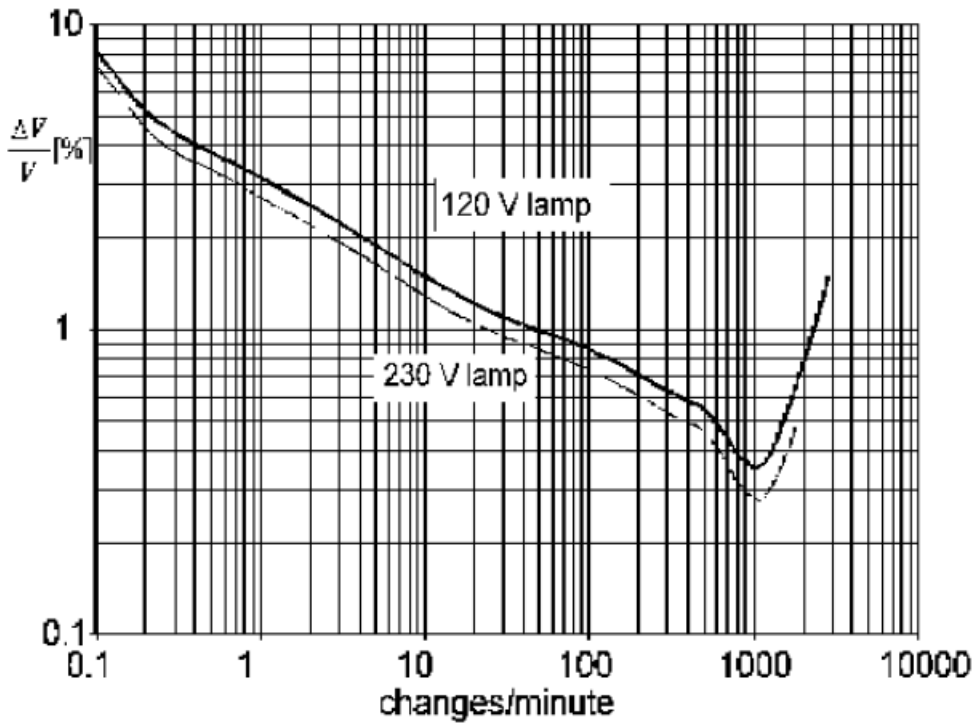


Figure 5—Comparison of flickermeter weighting curves for different voltage levels

5.3 Flicker performance of different lamp types

There is a need to understand the flicker performance of new lighting technologies such as CFLs (compact fluorescent lamps) and LED (light emitting diode) lamps especially with their ever-increasing penetration levels in electricity networks. The human eye has different perception thresholds for different lamp types as documented in a publication by EPRI on the testing that it carried out on different lamp types (PQTN Brief No. 24 [B31]). The lamps that were tested included the following:

— Two four-foot fluorescent fixtures with electronic ballasts (64 W and 80 W)

— Two CFLs with magnetic ballasts (13W and 15W)

— One 15 W CFL with an electronic ballast

— One 45 W halogen lamp

— One standard 60 W incandescent bulb

The averaged test results for this limited survey of six human subjects are shown in Figure 6. It shows the average perceptibility to three different levels of frequency modulation in the voltage supplied to the five types of light fixtures for six human subjects. It may be noted that the values for the incandescent lamp are illustrated as horizontal lines and there are two test samples each for 4-ft fluorescent fixtures with electronic ballasts and CFLs with magnetic ballasts. It can be seen that with exception of a CFL with magnetic ballast, the incandescent lamp is the most sensitive to flicker. An IEC-compliant flickermeter described earlier in the document is designed and calibrated for incandescent lamps and is therefore not suitable for other lamp types.

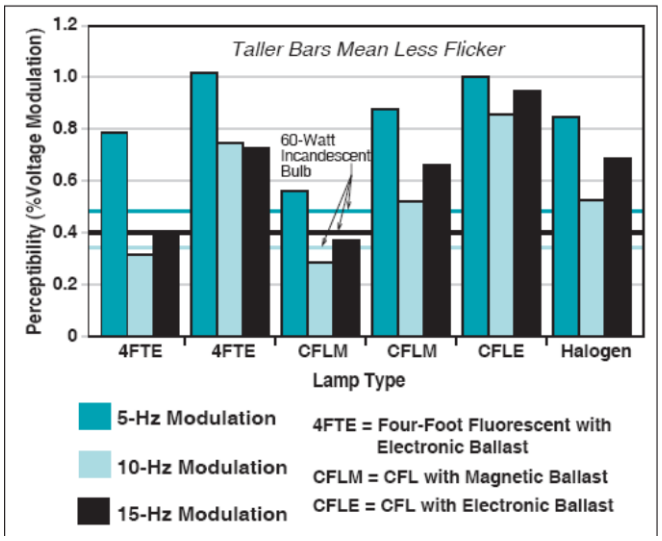


Figure 6—Test results on perception thresholds of humans

Gain factor (GF) is a measure that may be used to quantify flicker performance of a lamp type and is computed as a ratio of percentage change in its light output (luminous flux Φ) to the percentage change in input voltage (U) as shown in Equation (7).

$$GF = \frac{\left(\frac{\Delta\Phi}{\Phi}\right)}{\left(\frac{\Delta U}{U}\right)} \tag{7}$$

A higher value of GF for a lamp signifies its greater sensitivity to flicker. The advantage of using this measure is that it disregards a factor of perception that is unique for each person. As a result, this approach allows comparison of lamp sensitivities in a systematic and reproducible manner.

EPRI used this approach in computing the gain factors for different lamp types in the mid-1990s (PQTN Brief No. 36 [B32]). Square wave modulation was used to simulate voltage variations at test frequencies of 10 Hz and 20 Hz. The testing involved eight observers and the following lamps:

— Two CFLs with magnetic ballast

— Two four-foot fluorescent

— One CFL with electronic ballast

— One 60 W incandescent lamp

The test results that included gain factor and perception were normalized based on incandescent lamps and are presented in Figure 7. It shows the correlation between gain factor measurement and human perception of the flicker.

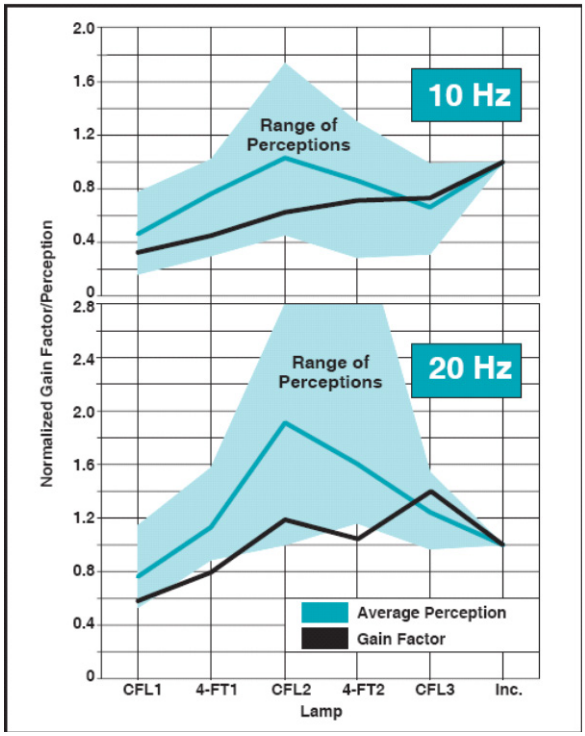


Figure 7—Quantifying flicker performance of lamps

Further tests (PQTN Brief No. 37 [B33]) were carried out by EPRI on 1995-vintage lighting products that included the following:

— Twenty-three CFLs (three samples each)

— Eleven 4-ft fluorescent fixtures (three samples each)

— 60 W, 120 V incandescent lamp

This testing encompassed a frequency range between 2 Hz and 25 Hz and the plot of resultant gain factors is shown in Figure 8. It is evident that, unlike for incandescent lamps, the gain factor of fluorescent fixtures is independent of frequency. Also, the average gain factor of a CFL is less than half that of an incandescent lamp at 8.8 Hz (most sensitive frequency for humans).

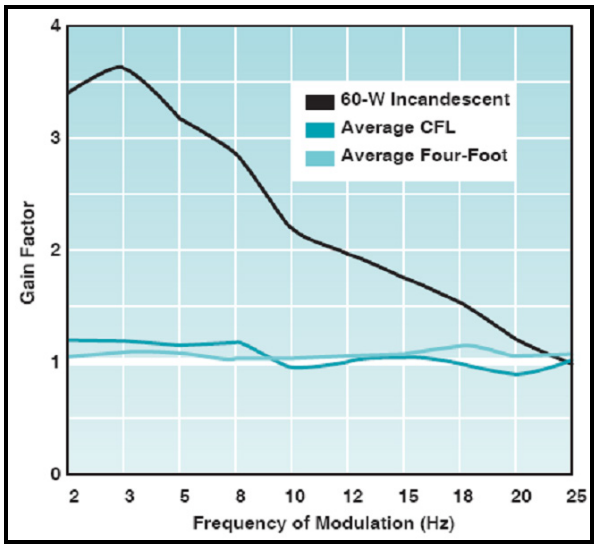


Figure 8—Gain factor variation over the test frequency range

The applicability of the findings presented previously to advances made in modern lighting technologies including CFL and LED lamps has been confirmed by the testing that was carried out in 2013 (Sharma and Sharp [B37]). Thus, it can be concluded that different lighting technologies differ in flicker performance. The IEC-compliant flickermeter described earlier in the document is designed and calibrated for incandescent lamps and is therefore not suitable for other lamp types. The authors of "Proposal for improving UIE/IEC Flickermeter" [B4] have suggested use of different weighting filters in Block 3 of the flickermeter to adapt it for other lamp types such as CFLs and LED lamps. One of the challenges is the unpredictability of the flicker performance of modern lighting, especially the prevalent dimmable technologies (Sharma and Sharp [B37]).

5.4 Impact of interharmonic voltages on light flicker

Interharmonics in power system can lead to oscillating luminous flux and thus become a source of light flicker (IEEE Task Force on Harmonics Modeling and Simulation [B20]). The references demonstrate the equivalence of Amplitude Modulation (AM) to the superposition of sinusoidal interharmonic components of proper amplitudes and phase angles to the fundamental (Langella and Testa [B25], Gallo, et al. [B6]). The IEC flickermeter standards only required testing with reference to amplitude voltage modulation, which was the first cause of light flicker identified.

For this reason, computations in IEC-compliant flickermeters are based on the measurement of fluctuations in RMS supply voltage producing light flicker on incandescent lamps. It means that these meters are capable of detecting light flicker only due to low-frequency interharmonics (below twice the fundamental frequency) as higher order interharmonics do not cause much RMS variation in incandescent lamps in absence of significant harmonics. Hence these meters have been found to be unable to properly measure light flicker produced by lamp technologies other than incandescent (Kim, et al. [B22], Slezingr [B40]).

Interharmonic voltage limits based on flicker (for frequencies up to 120 Hz for 60 Hz systems) were introduced in IEEE Std 519™-2014 [B18] (see Figure 9). In some other specific cases involving lamp technologies different from incandescent and a wider frequency range, interharmonic-flicker curves in IEEE Std 519-2014 [B18] and Tayjasanant, Wang, and Xu [B42] may be consulted.

Annex A reports some information about the impact of interharmonics on the light flicker produced by lamps technologies different from incandescent and on the performance of flickermeters. Firstly, the perfect equivalence between amplitude modulation and interharmonics is graphically explained; then, interharmonic-flicker curves (Tayjasanant, Wang, and Xu [B42]), experimentally obtained on different types of lamp technologies (Drapela, J., and P. Taman [B5], Slezingr, J. and J. Drapela [B40]) are used to show interharmonic voltage magnitudes producing $P_{st} = 1$. Finally, compact analytical formulae are used (Gallo [B6]) to illustrate IEC flickermeter response to interharmonics.

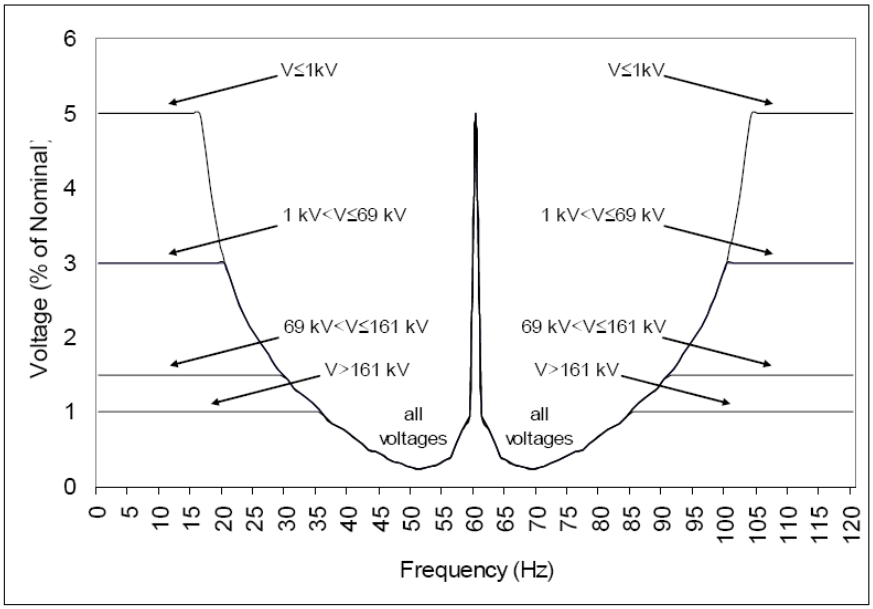


Figure 9—Interharmonic voltage limits based on flicker for frequencies up to 120 Hz for 60 Hz systems (IEEE Std 519 [B18])

6. Recommendations for flicker limits and evaluation procedure

This clause summarizes recommended planning levels and the procedure for determining and compliance of emission limits for individual customers. Different planning levels are recommended for different voltage levels. The emission limits applied to individual customers are developed based on these "planning levels," which are developed in IEC 61000-3-7.

Four different voltage levels are defined in Table 1 and the flicker planning levels are developed. This document deals primarily with planning levels at MV (medium voltage) and HV-EHV (high voltage to extra high voltage) because these are usually the voltages at the PCC with customers that may have fluctuating loads. These planning levels are designed to make sure that the flicker levels at LV connection points do not actually exceed the "compatibility level" that is defined to help ensure proper operation of customer equipment.

Table 1—System voltage levels

System	System voltage (V_r)
LV	$V_r \leq 1$ kV
MV	1 kV < $V_r \leq 35$ kV
HV	35 kV < $V_r \leq 230$ kV
EHV	$V_r > 230$ kV

6.1 Planning levels

6.1.1 Indicative values

The planning levels (denoted as L_{Pst} and L_{Plt}) recommended for PCCs at MV, HV, and EHV systems are shown in Table 2. The planning levels are developed to be the basis for applying emission limits for individual customers with PCC at these different voltages. The individual customer emission limits are developed using a procedure that allots each customer some portion of a planning level after allowing for flicker that propagates from other network voltage levels (or locations). Emission limits for individual loads (denoted as E_{Pst} and E_{Plt}) are set so that their aggregate effects do not cause overall flicker at PCC to exceed an adopted planning level.

Table 2—Recommended planning levels

	Flicker planning levels	
	MV	**HV-EHV**
L_{Pst}	0.9	0.8
L_{Plt}	0.7	0.6

These planning levels assume unity transfer coefficient (less than 1.0 in practice) between MV or HV systems and LV systems and may need upward adjustment as follows.

Transfer coefficient of flicker between two points A and B with dominant flicker source at point A is the level of flicker that can get transferred between the two points. It is defined as the ratio of the P_{st} values measured at the same time in the two locations as shown in Equation (8):

$$T_{PstAB} = \frac{P_{st}(B)}{P_{st}(A)} \tag{8}$$

The methods to compute transfer coefficient in the absence of any measurements are detailed in Annex B. An example of the impact of the transfer coefficient (T_{PstHL}) between HV and LV having a value of 0.9 is reflected in the revised indicative planning level for HV system as shown in Equation (9):

$$L_{PstHV\_revised} = \frac{L_{PstHV}}{T_{PstHL}} = \frac{0.8}{0.9} = 0.89 \tag{9}$$

These planning levels are selected to help ensure that the compatibility levels are not exceeded at LV locations where lighting loads are connected. Note that compatibility levels are not actually defined for the MV, HV, and EHV levels since lighting customers are not directly connected at these levels. The compatibility levels for LV are 1.0 for $P_{st95\%}$ and 0.8 for $P_{lt95\%}$.

6.1.2 Evaluation—assessment procedure

The following procedure is recommended for ongoing evaluation against the chosen planning levels. The procedure is based on continuous monitoring of a continuous fluctuating load (or monitoring when the fluctuating load is active) with an instrument that is compliant with IEC 61000-4-15 for a full week. It is suggested that the following procedure may be repeated for each phase. Alternatively, the individual values for all the three phases may be combined for the collective analysis if the loading is known to be balanced.

1) Obtain an array of P_{st} values for each day resulting in 144 values for each phase.

2) Calculate an array of P_{lt} values for each day. Each P_{lt} value is calculated from twelve P_{st} values spaced 10 minutes apart using a cubic relationship as described in Equation (6). It is recommended that sliding window approach be used in which the oldest P_{st} measurement is replaced by the newest P_{st} value at each 10 minute interval resulting in 144 P_{lt} values in a day for each phase. The statistical analysis in the subsequent steps should be carried out after carrying out the necessary filtering to exclude faults and other non-load created voltage fluctuations.

3) Combine the P_{st} values for a full week (Sunday midnight to Sunday midnight), resulting in 1008 values for each phase and calculate summary statistics for the week.

   $P_{st99\%}, P_{st95\%}$

4) Combine the P_{lt} values for a full week (Sunday midnight to Sunday midnight), resulting in 1008 P_{lt} values for each phase when the sliding window approach is used, and calculate P_{lt} summary statistics for the week.

   $P_{lt99\%}, P_{lt95\%}$

5) The statistical values calculated represent the actual flicker levels. These can be compared with the system flicker planning levels.

   1) 95% probability value should not exceed the planning level.

   2) 99% probability value may exceed the planning level by a factor (1−1.5) depending on system conditions to be determined by the system operator.

6.2 Determining individual customer emission limits

A detailed procedure for determining emission limits for fluctuating loads connected to MV, HV, and EHV systems is provided in IEC 61000-3-7. It is important to ensure that the fluctuating loads stay in continued compliance with their determined emission limits and the guidelines and recommended approach for the same are presented in 6.3.

6.3 Evaluating compliance with emission limits

Flicker contribution of a facility is typically assessed at its defined PCC. The example of PCC is graphically illustrated in Figure 10, which shows a common scenario of a facility employing fluctuating loads being served off a radial feeder.

In this case, the metering point A is nearest to the PCC and provides the worst-case fluctuations that may be seen by a neighboring customer. Metering point B provides data at the substation level, and is a measure of what is seen by other feeders on that substation.

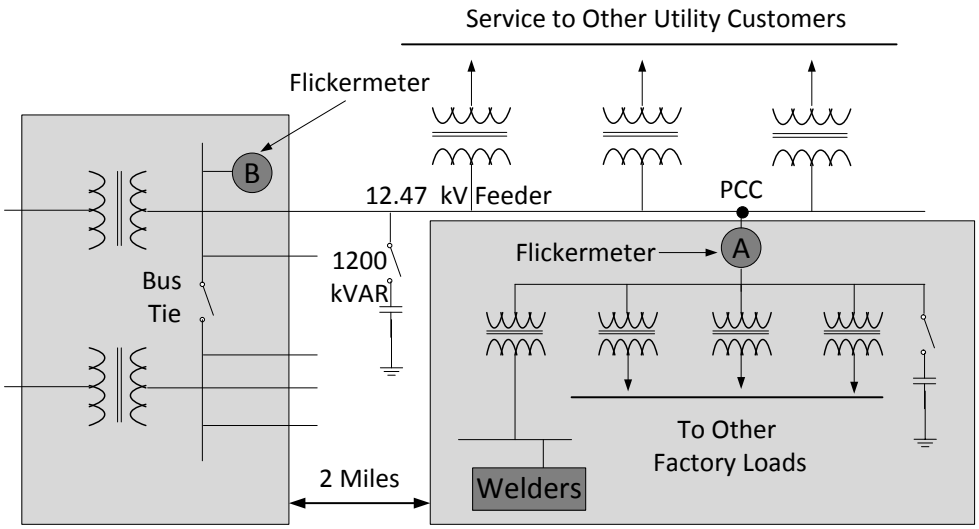


Figure 10—PCC Illustration

The following evaluation procedure is recommended for ongoing assessment of compliance with the flicker limits at the PCC. The procedure is based on continuous monitoring with an instrument that is compliant with IEC 61000-4-15 [B14]. It is suggested that the following procedure may be repeated for each phase. Alternatively, the individual values for all the three phases may be combined for the collective analysis if the loading is known to be balanced. The procedure is performed based on a weekly evaluation of customer compliance with flicker limits.

a) Make the necessary adjustments in specified customer emission limits for the system short-circuit capacity. If the short-circuit capacity during the period of the measurements is lower than the level specified in the customer contract, then an adjustment should be performed as follows:

$$E_{Pst\_actual} = E_{Pst\_contract} \times \frac{S_{sc\_contract}}{S_{sc\_actual}} \tag{10}$$

where

E_{Pst} is the customer emission limit

S_{SC} is the short-circuit capacity

Term *contract* in the subscript refers to the contract level and *actual* refers to the period of measurements.

b) Obtain an array of P_{st} values for each day resulting in 144 values for each phase.

c) Calculate an array of P_{lt} values for each day from the P_{st} values in previous step. It is recommended that sliding window approach be used in which the oldest P_{st} measurement is replaced by the newest P_{st} value at each 10 minute interval resulting in 144 P_{lt} values in a day for each phase. The statistical analysis in the subsequent steps should be carried out after carrying out the necessary filtering to exclude faults and other non-load created voltage fluctuations. A sample flicker trending at PCC of a facility running a fluctuating load is shown in Figure 11. It identifies a high P_{st} value that is attributed to a network fault event that needs to be excluded for assessing flicker contribution of the facility.

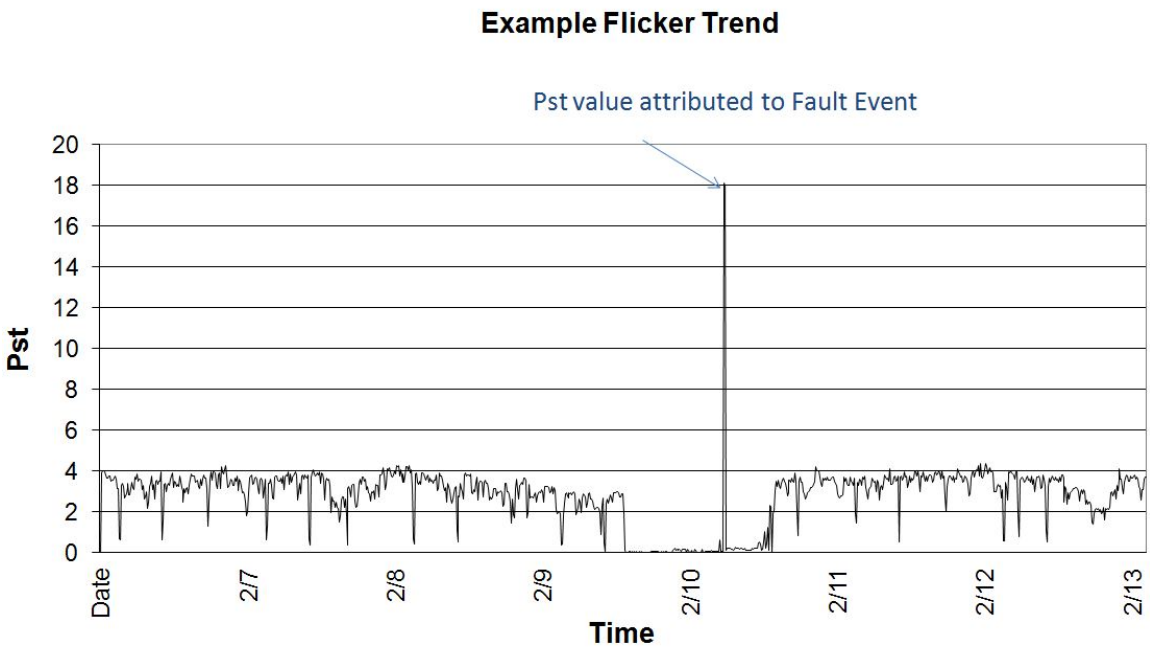


Figure 11—Example flicker trend due to fluctuation load impacted by network fault event

d) Combine the P_{st} values for a full week (Sunday midnight to Sunday midnight) and calculate summary statistics for the week (maximum 1008 values).

$P_{st99\%}$, $P_{st95\%}$

e) Combine the P_{lt} values for a full week (Sunday midnight to Sunday midnight) and calculate summary statistics for the week (maximum 1008 values based on a sliding window).

$P_{lt99\%}$, $P_{lt95\%}$

f) The statistical values calculated represent the actual flicker levels. We will refer to these values obtained from the direct measurements as follows (general term for each P_{st} index, same terminology can be applied to the P_{lt} indices).

P_{st_actual}

g) Calculate the estimated contribution of the customer ($P_{st\_customer}$) to the flicker levels. The procedures for estimating contribution of single customer are presented in 6.4.

h) These statistics can be compared with the adjusted customer emission limits.

   1) 95% probability value should not exceed the emission limit.

   2) 99% probability value may exceed the emission limit by a factor (1−1.5) depending on system conditions to be determined by the system operator.

6.4 Estimating flicker contribution of single customer

In order to estimate the flicker contribution made by an individual customer, it is necessary to exclude the contribution of the background flicker in the system. The following methods are recommended depending on the magnitude of background levels.

6.4.1 Low background flicker levels

If the background levels are low ($P_{st\_background} \leq 0.5$), the flicker being caused by the new customer can be estimated by the following method:

Assume that the limit (99th percentile) for the acceptable level of flicker at the PCC for a new customer is set at E_{Pst}.

Measure the background levels of flicker before connecting the customer (this should be 99th percentile value computed over at least a two week period). The value thus obtained is $P_{st\_background}$.

Finally, the actual levels of flicker (99th percentile) after connecting the customer are measured at P_{st_actual}.

In most cases, the flicker that is caused by the new customer can be estimated by assuming the flicker levels add using cubic summation.

$$P_{st\_customer} = \sqrt[3]{P_{st\_actual}^3 - P_{st\_background}^3} \tag{11}$$

This value can be compared with the customer flicker limit.

$P_{st\_customer}$ should be less than E_{Pst}

As a practical measure, the background flicker will typically have to be measured before the new fluctuating load starts up. A two week measurement period prior to startup would be reasonable. The background levels can also be checked periodically during any plant shutdowns.

6.4.2 High background flicker levels

If the background flicker levels are substantial ($P_{st\_background} > 0.5$), the method in 6.4.1 can result in significant errors. One method that involves correlation between the fluctuating current and the observed voltage fluctuations to determine the emission level of a particular fluctuating load is presented here.

In cases where multiple flicker-producing facilities are fed from the same supply, the most reliable method of assessing the flicker contribution from each source is to remove one of the contributors from the circuit and measure only the flicker from the other. This is not often practical and the following method may be suitable for identifying flicker contribution of individual sources.

The underlying principle of the approach is that the customer contribution to the overall flicker levels can be correlated to the current drawn by it with the utility source impedance being the correlation coefficient. Any voltage variation that is not related to a current variation, through the utility impedance, must therefore be coming from the utility system itself.

It may be noted that point of evaluation (POE) for this method may not be the actual PCC. The procedure for the implementation of this approach is presented here (refer to Figure 12). It may be noted that the algorithm itself will have to be implemented in a time-domain modeling and simulation platform:

a) Measure the voltage waveform ($V_M(t)$) at the point of evaluation (POE) and current waveform ($i_M(t)$) drawn by the flicker source.

b) Use $V_M(t)$ to compute P_{st_POE} using IEC method [B14]. This represents the overall flicker levels at the POE.

c) Compute emission voltage $V_E(t)$ using flicker source current, utility source impedance and a constant utility open circuit voltage (assumed). It represents the voltage that would appear at POE if this was the only source of voltage fluctuations.

$$V_E(t) = V_R(t) - R_S \times i_M(t) - L_S \times \frac{di_M(t)}{dt} \tag{12}$$

where

$V_R(t)$ represents the voltage at the monitoring point if the system was unloaded and whose angle should be equal to that of the voltage waveform $V(t)$ computed using the Equation (13).

$$V(t) = V_M(t) + R_S \times i_M(t) + L_S \times \frac{di_M(t)}{dt} \tag{13}$$

d) Use $V_E(t)$ to compute $P_{\text{st\_emission}}$ using IEC method. This is the flicker that can be attributed to the customer.

In case POE is different from PCC, the flicker will have to be estimated at PCC from those obtained at POE by taking into account the circuit impedance between the two locations.

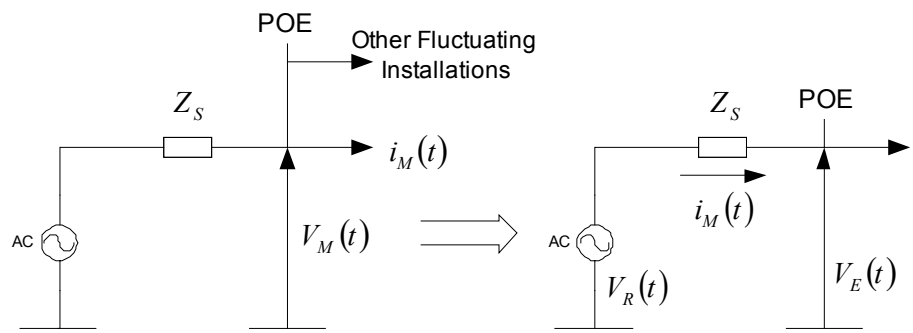


Figure 12—Measurement-based approach for estimating flicker contribution of single customer

6.5 Rapid voltage change

Voltage changes due to events such as motor starting, capacitor switching, and voltage regulator switching are classified as rapid voltage changes (RVC) as the changes are sustained over several cycles (see Figure 13). Bollen, et al [B2] shows that existing flicker indices may not accurately indicate objectionable flicker due to RVCs, often because they occur infrequently. The indicative planning levels in Table 3 (from IEC 61000-3-7) may be used to determine emission limits for such changes for individual customers based on the number of changes.

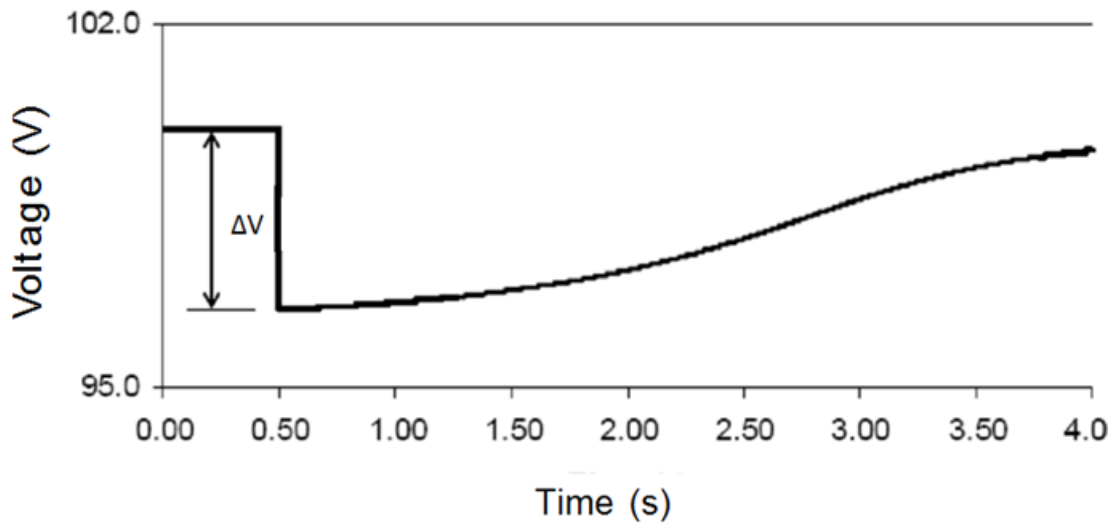


Figure 13—Example rapid voltage change due to motor starting (IEC 61000-3-7)

Table 3—Indicative planning levels for rapid voltage changes (IEC 61000-3-7)

Number of changes, N	ΔV/Vr (%)	
	MV	HV-EHV
N ≤ 4 per day	5−6	3−5
N ≤ 2 per hour	4	3
2 < N ≤ 10 per hour	3	2.5

Planning levels for RVC may vary from those in Table 3 based on several factors of the RVC. Bollen, et al. [B2] shows that definitions are needed to help ensure reliable categorization of the RVC, and provide recommended values for each. Public perception of the RVC will vary depending on the following:

a) The duration of a steady state condition (between two voltage change characteristics)

b) The rate of change of the voltage (dv/dt)

c) The magnitude of the voltage change

7. Estimating flicker levels at PCC of facilities serving fluctuating loads

For pre-evaluation of potential flicker-producing loads, simplified methods can be used. For example, shape factors can be used to translate some typical modulation waveforms into equivalent sine or square wave modulating waveforms in order to make use of "P_{st} = 1 curve" (Figure 5 and Table 4) for estimating flicker levels. This method is only suitable where the load and the resultant voltage profile at PCC is cyclic e.g., regular motor starting, rolling mill, and resistive spot welding.

Table 4—P_{st} = 1 test points for rectangular voltage fluctuations (Walker [B46])

Col.1 Changes per minute	Col.2 Fluctuation Frequency Hz	Col.3 Pst=1 Relative voltage changes for unit flicker severity for 230 V lamps ΔV/V (%)	Col.4 Pst=1 Relative voltage changes for unit flicker severity for 120 V lamps ΔV/V (%)
0.1	0.000833	7.400	8.202
0.2	0.001667	4.580	5.232
0.4	0.003333	3.540	4.062
0.6	0.00500	3.200	3.645
1	0.00833	**2.724**	**3.166**
2	0.01667	**2.211**	**2.568**
3	0.02500	1.95	2.250
5	0.04167	1.64	1.899
7	0.05833	1.459	1.695
10	0.0833	1.29	1.499
22	0.1833	1.02	1.186
39	0.3250	**0.906**	**1.044**
38	0.4000	0.87	1.000
68	0.5667	0.81	0.939
110	0.9167	**0.725**	**0.841**
176	1.4667	0.64	0.739
273	2.2750	0.56	0.650
375	3.1250	0.50	0.594
480	4.0000	0.48	0.559
585	4.8750	0.42	0.501
682	5.6833	0.37	0.445
796	6.6333	0.32	0.393
1020	8.5000	0.28	0.350
1055	8.7917	0.28	0.351
1200	10.000	0.29	0.371
1390	11.583	0.34	0.438
1620	13.500	**0.402**	**0.547**
2400	20.000	0.77	1.051
2875	23.9583	1.04	1.49

7.1 Use of shape factors

The flicker severity can be computed using the following equation:

$$P_{ST} = \left(\frac{d}{d_{Pst=1}} \right) \times F \tag{14}$$

where

F is a shape factor (see Annex C). For motor-starting without inrush mitigation, a value of unity may be used for F.

Relative voltage change (d) can be evaluated as the ratio of load power change (ΔS_i) to the short-circuit power (S_{SC}). The following equation may be used for balanced three-phase loads:

$$d = \frac{\Delta V}{V_r} \approx \frac{\Delta S_i}{S_{SC}} \tag{15}$$

For motor starting evaluation, ΔS_i is the maximum apparent power during the start.

For a two phase load (e.g., welding load), the following equation may be used:

$$d = \frac{\sqrt{3} \times \Delta S_i}{S_{SC}} \tag{16}$$

For systems with low X/R (less than 5), use Equation (17) as follows:

$$d = \frac{R_L \times \Delta P + X_L \times \Delta Q}{V_r^2} \tag{17}$$

The variable $d_{Pst=1}$ in Equation (14) represents the relative voltage change that will yield P_{st} value of 1.0 corresponding to the number of voltage changes per minute due to the load operation. This value can be obtained using the plot in Figure 5.

7.1.1 Rolling mill

A rolling mill example is presented here from IEC 61000-3-7. The expected voltage profile at PCC due to the operation of the mill is shown in Figure 14.

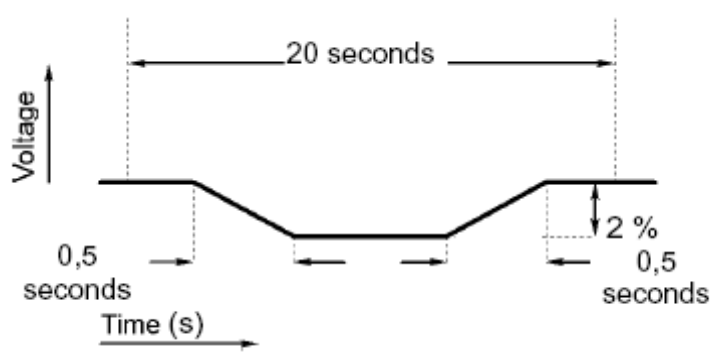


Figure 14—Expected voltage profile at PCC due to rolling mill (IEC 61000-3-7)

Relative voltage change (d) = 2 %

Shape factor (F) = 0.31 (from Figure C.2)

Number of voltage changes in one minute = 6 (2 in 20 s)

$d_{Pst=1}$=1.9 (from Figure 5 for 120 V system)

$$P_{ST} = \left(\frac{d}{d_{Pst=1}}\right) \times F = \left(\frac{2}{1.9}\right) \times 0.31 = 0.325 \tag{18}$$

7.1.2 Resistive spot welding

Resistive automated spot welders are also a source of voltage fluctuations, which can cause flicker if the fluctuations are severe enough. A typical cycle involves the passage of a high current through work pieces to be joined followed by a period when the current is switched off. The nature of the resultant voltage fluctuations in feeding system is such that they have constant shape and repeat at fixed time intervals. Thus, the shape factor method may be used to get an estimate of the flicker due to a spot welding operation.

An example of the voltage drop at the PCC due to an automated spot welder operation is shown in Figure 15. The welding current flows for a duration of 0.1 s and the cycle repeats every 0.2 s.

Relative voltage change (d) = 0.5 %

Shape factor (F) = 1.375 (from Figure C.1)

Number of voltage changes in one minute = 600

$d_{Pst=1}$=0.5 (from Figure 5 for 120 V system)

$$P_{ST} = \left(\frac{d}{d_{Pst=1}}\right) \times F = \left(\frac{0.5}{0.5}\right) \times 1.375 = 1.375 \tag{19}$$

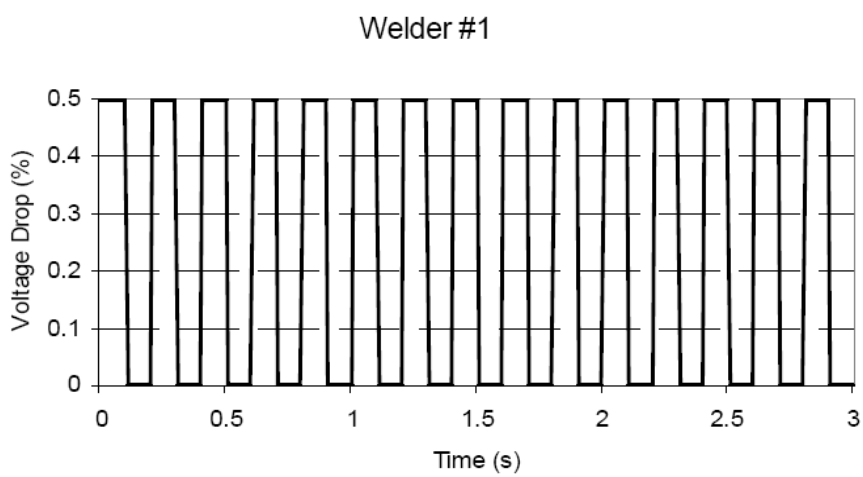


Figure 15—Voltage drop at PCC due to welder operation (IEC 61000-3-7)

A simulation-based approach should be used for an accurate assessment especially if multiple automated welders are operating in parallel. The following measures may be considered in order to reduce the flicker levels due to the resistance spot welding operation:

— Separate the supply mains feeding resistance welding machines from other networks, in particular the lighting power supply, with the use of isolation transformers.

— Connect the welding machines to the highest possible supply voltage.

— When there are several welding machines, connect the single-phase machines to three phases in a manner to obtain a balanced load on the three phases.

— If only the customer who uses the welder is disturbed, and if a single-phase welder is used, use the phase(s) that is (or are) not disturbed to feed the lighting devices.

— Reduce the "heat" of the weld to a minimum acceptable level. It is not uncommon to find welding machines with their heat at a higher set-point than is required to produce a quality weld.

— For single large welders, re-sequence the firing of the electrodes (if possible) so that the welding machine draws more frequent but smaller pulses of current to produce the welds (PQTN Case Study No. 1 [B30]).

— For multiple small welders special sequencing equipment is often used to prevent several welders from firing at the same time. Usually, this can be done by delaying the firing for a few cycles in a controlled manner. This prevents random flicker producing events and may not cause a noticeable slow down in the welding process.

The shape factor method is not suitable for predicting flicker due to loads such as arc furnaces where the voltage fluctuations are random and irregular. For such loads, the method based on the actual measurements is presented in the next subclause.

7.2 Estimating flicker levels for arc furnaces

Electric furnaces have been used in both ferrous and non-ferrous industries. In the ferrous industry, electric arc furnaces (EAFs) are typically used to melt ferrous material in the production of steel while submerged arc furnaces (SAFs) and other similar electric furnaces are used in the non-ferrous industry to smelt the charge to produce platinum, nickel, calcium carbide, and others. In both the ferrous and non-ferrous industries, a ladle metallurgical furnace (LMF) is often used to adjust the chemical properties of the liquid metal and electrically reheat the metal to the correct temperature before transforming it into a solid, semi-finished state, typically through continuous casting (ferrous industry) and shotting (non-ferrous industry). This document mainly talks about EAFs as excessive flicker is mainly a concern with this type of electric furnaces.

The electric arc furnace is a major source of perturbations on the high voltage network. It creates an electric arc between electrodes and scraps of steel, which are melted from the heat created by the arc. Arc furnaces have melting cycles that last on the order of 30 min to 2 h, creating random variations in the voltage. As the melting cycle changes from full melt to refining, the arc length is reduced and the flicker is reduced accordingly. The frequency spectrum of the disturbances from an arc furnace has a broad band.

Estimates of the expected flicker levels resulting from a new arc furnace facility can be developed from measurements of flicker levels associated with other arc furnace facilities around the world. As flicker is a function of the lamp voltage rating, different weighting factors are used for the different voltage levels (e.g., 230 V in Europe) around the world.

7.2.1 Short-circuit voltage depression

A number of parameters associated with the arc furnace installation and the supply system affect the flicker levels that can be expected at the PCC.

The main supply system parameter affecting the flicker that results from arc furnace installations is the short-circuit capacity at the PCC. A method of characterizing this short-circuit capacity in terms of the size of the furnace is the short-circuit voltage depression (SCVD) and is shown in Equation (20).

$$SCVD = \frac{\nabla V}{V}(\%) = \frac{Scc_f}{Scc_n} \tag{20}$$

where

Scc_f = Short-circuit capacity of the furnace at the PCC (electrodes shorted)
Scc_n = Short-circuit capacity of the system at the PCC (short circuit at the PCC)

In order to calculate the furnace short-circuit level (electrodes shorted), it is necessary to obtain data from the facility design for the transformer impedances, cable impedances, electrode lead inductances, and any additional series inductance in the circuit (high reactance designs). Without further information, it is often assumed that the short-circuit MVA with the electrodes shorted is on the order of two times the rated MW capacity of the furnace (for ac arc furnaces). The concept of the short-circuit level with the electrodes shorted is not as applicable for a dc furnace and assumes a short-circuit level of two times the MW rating is not a reasonable approximation for dc furnaces to facilitate estimating flicker effects.

Measurements have been performed around the world to characterize the $P_{st99\%}$ levels for different ac arc furnace facilities. Figure 16 illustrates some of these results that were carried out in Belgian HV systems as a function of the short-circuit voltage depression level (without compensation) (Robert, A. and M. Couvreur [B36]). It is clear that there is a direct relationship between the flicker severity and the short-circuit voltage depression level.

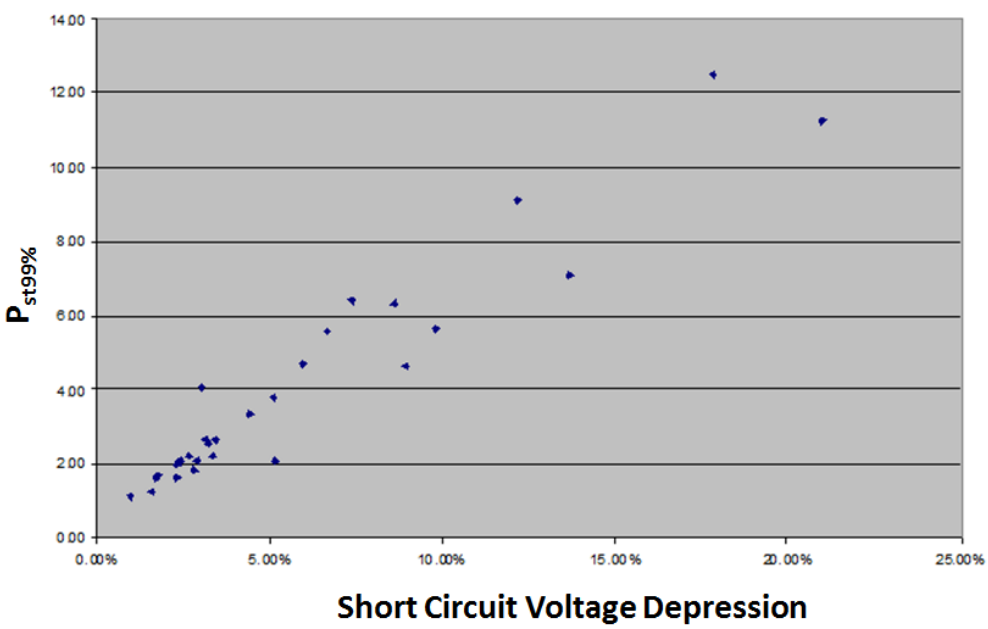


Figure 16—$P_{st99\%}$ levels as a function of the SCVD level for ac arc furnace facilities

7.2.2 Electric arc furnace K_{st}

The relationship between the flicker severity and the short-circuit voltage depression level for an arc furnace has been given the term K_{st}.

$$K_{st} = \frac{P_{st95\%}}{SCVD} = \frac{P_{st95\%}}{Scc_f / Scc_n} \tag{21}$$

K_{st} is a measure of the arc furnace flicker causing characteristics independent of the effect of the short-circuit strength. Figure 17 illustrates K_{st} values plotted as a function of the arc furnace size. For 120 V systems, a value ranging between 58 and 70 for K_{st} is recommended for estimating purposes. A value of 85 is commonly used for stainless steel. However, it should be noted that values of more than 100 have been shown to exist (Robert and Couvreur [B34], Horton, Haskew, and Burch [B13]).

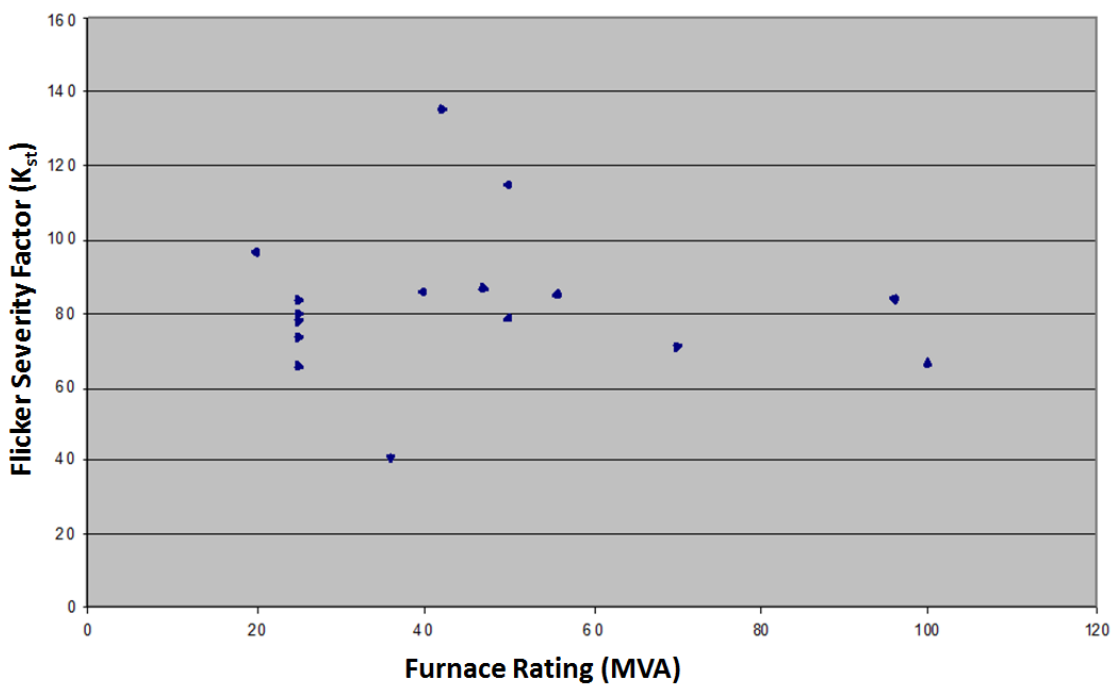


Figure 17—Flicker severity factor as a function of the furnace MVA rating

It may be possible to obtain estimated K_{st} values from the arc furnace supplier. Many factors influence this value, including furnace control characteristics, type of steel to be melted, reactance values for control of the arc, transformer tap characteristics, melting process, etc.

7.2.3 Correction for type of furnace

During the process of estimating flicker from an electric furnace, correction may be applied to the estimate for furnace designs other than typical ac arc furnaces.

For example, it is possible to reduce flicker levels with a high reactance furnace design. However, less empirical data is available to come up with assumptions for the amount of flicker reduction that is typical. Therefore, expected K_{st} values for these types of furnace designs should be obtained from the manufacturer.

Then, dc arc furnace is similar to the ac furnace except that its arc is more stable and usually causes less flickering for the same size furnace. It is typically assumed that dc arc furnaces will have about 50−75% of the flicker levels associated with a similar size ac furnace. The submerged arc furnaces (SAF) usually draw an arc on or in a significant amount of slag. The resistance of this slag prevents true short circuits as one sees during an EAF operation. Consequently, their K_{st} values are much smaller than a similarly rated EAF furnace. Typical values are in the 5 to 30 range.

The electric ladle furnaces are used for secondary refining of the metals exiting the main furnace, such as EAF, SAF, basic oxygen furnaces, etc. They operate in a much more stable mode than the electrical arc furnaces, since in their operation the arc is established on a top of a molten metal that is usually covered by a thin slag layer. Typical K_{st} ranges for such furnaces are in the 15 to 30 range.

7.2.4 Effect of compensation equipment

Static var systems can be used to help control flicker levels from the arc furnace operation. Conventional static var systems with thyristor-controlled reactors can typically provide a reduction factor of around two. However, the amount of flicker reduction is very dependent on the SVC size and control characteristics.

In case a higher reduction factor is desired, another compensator type known as STATCOM (static compensator) may be considered. These systems can be designed to compensate for reactive power fluctuations with much faster response time in comparison to static var systems.

In addition to the shunt compensation equipment mentioned previously, another option that can be employed is usage of a reactor that is connected in series with the furnace load [B45]. These are typically tapped devices and are intended to smooth out the current, as well as the power variation of a furnace load resulting in flicker mitigation. However, they will have a direct effect on the furnace operation, such as reduced output due to voltage drop.

7.2.5 Summary of important factors for estimating flicker levels

Table 5 summarizes the reduction factors that may be incorporated in the calculations provided in 7.2.2 for estimating the flicker level for a particular arc furnace facility. Note that a combination of multiple options will provide a better reduction factor than of a single option. However, their effect will not be a summation of what one can achieve by each option alone.

Table 5—Factors affecting the flicker levels resulting from an arc furnace installation

Factor description	Reduction factor value
Correction for furnace type—high reactance design	1.0−1.25
Correction for furnace type—dc arc furnace	1.5−2.0
Effect of conventional static var system	1.5−2.0
Effect of STATCOM	3.0−6.0
Effect of series reactor	1,0–1.25

7.3 Summation effect for multiple sources

In case of multiple sources of flicker, the following summation rule can be used to estimate the overall flicker levels at PCC for different types of the loads.

$$P_{st} = \sqrt[m]{\sum_i P_{sti}^m} \tag{22}$$

where,

m is summation law exponent

m = 4 for arc furnaces run that avoid coincident melts
m = 3 if risk of coincident voltage changes is small
m = 2 if coincident stochastic noise is likely to occur, for example coincident melts on arc furnaces
m = 1 if there is a very high occurrence of coincident voltage changes

In most cases involving little knowledge of the risk of coincident voltage changes, m = 3 may be used as it has been found to give conservative results and is generally accepted.

8. Customer agreements

In this clause, guidelines for customer agreements are provided that can be the basis for defining relative responsibilities and assessment methods for customer installations that may cause flicker problems.

8.1 Flicker requirements

8.1.1 Limits

Flicker will be assessed at the PCC using an instrument in compliance with IEC 61000-4-15. The example customer contribution (emission limits) to the flicker measured at the PCC shall be 0.8 or less for the short term flicker (P_{st}) and 0.6 or less for the long-term flicker (P_{lt}).

Based on the measurement period of at least a week, the following criteria should be met for compliance:

— 95% probability value should not exceed the emission limit.
— 99% probability value may exceed the emission limit by a factor (1−1.5) depending on system conditions to be determined by the system operator.

8.1.2 Prior to startup

The following information must be offered by the electrical energy supplier:

— Short-circuit power at the PCC

— Background flicker level

— Planning level at the voltage level where the connection takes place

If background flicker levels are a possible concern, background levels ($P_{stbackground}$) will be measured before the facility start up. A two-week measurement period prior to the start-up can be used for this characterization.

If possible, the customer should provide an estimate of the flicker levels (P_{st} and P_{lt}) that are likely once the plant begins normal operation. If the flicker levels are expected to exceed the allowable limits, the planned mitigating steps and the expected improvements should be described. Also, a detailed study may be warranted if the expected flicker levels are expected to be approaching the permissible limits.

The following information may be requested from the customer about the planned facility load:

— Maximum load power (S_{max})

— Load power variation (ΔS)

— Number of variations per minute (r)

— Alternatively, the K_{st} value for loads such as arc furnaces should be provided

In the case of an electric arc furnace facility, the following information may also be requested to estimate the expected flicker levels using the methodology in Clause 6.

— Furnace type—dc/ac

— High reactance design (yes/no)

— Furnace MW rating

— Furnace K_{st}

— Mitigating technology planned—SVC/STATCOM

8.1.3 Compliance on an ongoing basis—after startup

After the plant is successfully connected to utility system, continuous monitoring of the flicker contributions of the customer can be used to ensure the compliance on an ongoing basis. The procedure is based on continuous monitoring with an IEC-compliant flickermeter and is presented in 6.3.

Annex A

(informative)

Impact of interharmonics on flicker related to non-incandescent lamps

A.1 Equivalence between interharmonics and amplitude modulation

A normalized voltage with a couple of superimposed interharmonic components characterised by the same amplitude a, symmetrical frequency positions with respect to it ($f_{ih1}=f_0-f_M$ and $f_{ih2}=f_0+f_M$) and initial phase angles such that $\varphi_{ih1}+\varphi_{ih2}=0$, is subject to a perfect amplitude modulation of amplitude $2a$ and a modulation frequency of f_M.

Figure A.1 shows three vectors (in black) representing the three aforementioned components. The vector representing the fundamental component is fixed while the two interharmonic components rotate in opposite directions at an angular speed that is proportional to f_M. The resulting vector will be amplitude modulated.

When there is a single interharmonic component of amplitude $2a$ at a frequency distance equal to f_M superimposed to the fundamental, it is possible to demonstrate (Langella and Testa [B25]) that the resulting vector will be a unity signal at angular frequency f_0, which is subject to an amplitude modulation of amplitude $2a$ and a modulation angular frequency f_M , added to a couple of interharmonics of amplitude a and phase angles producing a prevailing phase modulation of the first term. Again, Figure A.2 shows the two vectors (in black) representing the fundamental and the interharmonic together with an additional two vectors in opposition (in dark gray) both rotating at $-f_M$. The resulting effect of the two additional vectors is null, but if one half of the vector representing the original interharmonic is combined with the upper additional vector and the other half is combined with the lower additional vector, a graphical interpretation of the double modulation is clear. Of course, the phase modulation does not produce any noticeable light flicker.

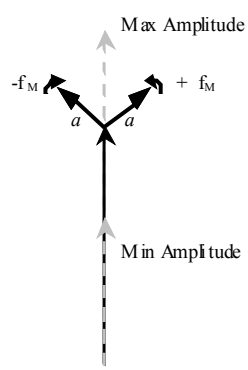


Figure A.1—Amplitude modulation

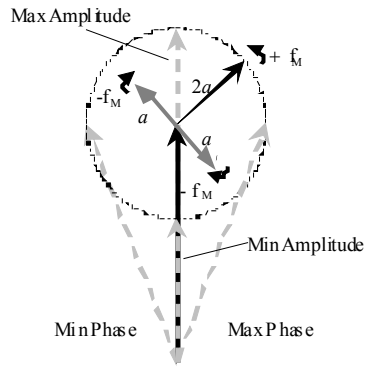


Figure A.2—Single interharmonic component

A.2 Interharmonics effects on Incandescent lamps

For sinusoidal supply, an incandescent lamp has an average flux component and a double frequency ($2f_0$) component, a variation that is not perceived by humans. But, in presence of an interharmonic, average luminous flux gets amplitude modulated as:

$$f_M = \left| f_0 - f_{ih} \right| \tag{A.1}$$

where

f_0 is fundamental frequency and
f_{ih} is interharmonic frequency

For interharmonics in the range up to $2f_0$ and low modulation frequencies ($f_M \leq 15$ Hz), there are enough RMS voltage fluctuations to cause flicker, which an IEC flickermeter is capable of detecting. Higher frequency interharmonics ($f_{ih} > 2f_0$) do not cause enough RMS variation to result in any flicker for incandescent lamps.

Figure A.3 reports interharmonic-flicker curves of incandescent and halogen lamps experimentally determined by utilizing a modified concept for measurement of a lamp gain factor in frequency domain and by utilizing the published limits on voltage flicker (Drapela and Taman [B5]). Experiments were conducted for 50 Hz systems superimposing a single interharmonic component to the fundamental. Thus, interharmonic-flicker curves of an individual light source determines for each interharmonic frequency its maximal acceptable interharmonic magnitude for which no light flicker can be perceived by the "average observer," that means the P_{st} is less than 1.

Halogen lamps are expected to substitute some of the classical incandescent lamps due to the similarity of their luminous flux. These lamps show a very similar behavior to incandescent lamps in the range from 0 Hz to 100 Hz. Moreover, they also show sensitivity to interharmonics of some percentages around the third harmonic.

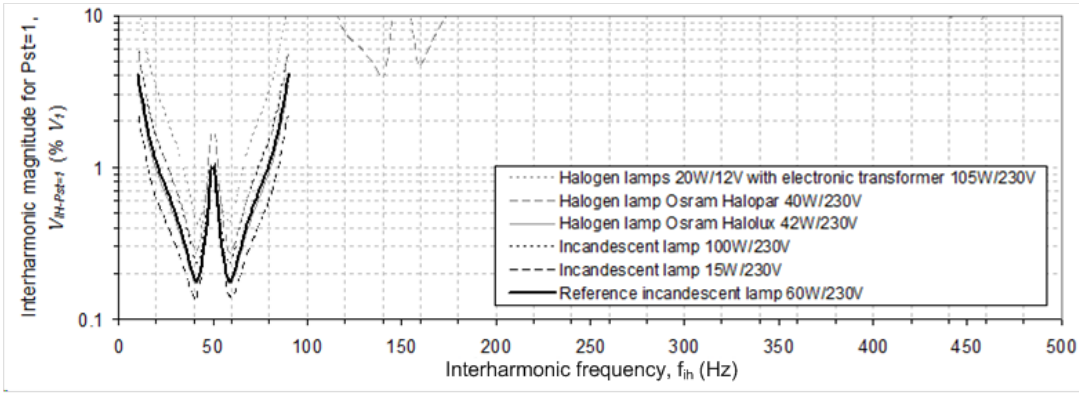


Figure A.3—Interharmonic-flicker curves of incandescent and halogen lamps

A.3 Interharmonics effects on non-incandescent lamps

Flicker performance of non-incandescent lamps (e.g., CFLs, LED lamps) has been compared with those of incandescent lamps in the presence of interharmonics in Kim et al. [B22], Drapela and Taman [B5], and Slezingr and Drapela [B40]. Experimental results (Kim, et al. [B22], Slezingr and Drapela [B40]) indicate that non incandescent lamps flicker immunity is similar to that of incandescent lamps for interharmonics below 2nd harmonic. These lamps continue to be sensitive to interharmonics around higher order harmonics (e.g., 3rd and 5th) differently from incandescent lamps This may be attributed to the use of magnetic ballasts and diode bridge rectifier in LED lamps and CFLs (Drapela and Taman [B5], Slezingr and Drapela [B40]).

Figure A.4 shows interharmonic-flicker curves of fluorescent and HID lamps operated with magnetic ballasts. It is observed that the presence of the non-linear component constituted by the lamp discharge makes the lamps sensitive to interharmonics at frequencies higher than 100 Hz of amplitudes starting from 1%. Similar observations can be made for linear fluorescent lamps operated with external electronic ballasts of different designs (see Figure A.5). For interharmonics at frequencies higher than 100 Hz, interharmonics of amplitudes around 0.5 % is enough to produce P_{st} =1.

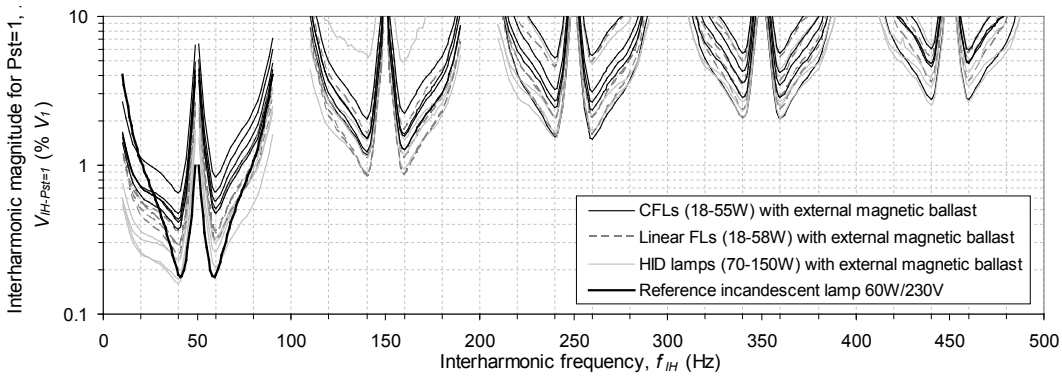


Figure A.4—Interharmonic-flicker curves of fluorescent and HID lamps operated with magnetic ballasts

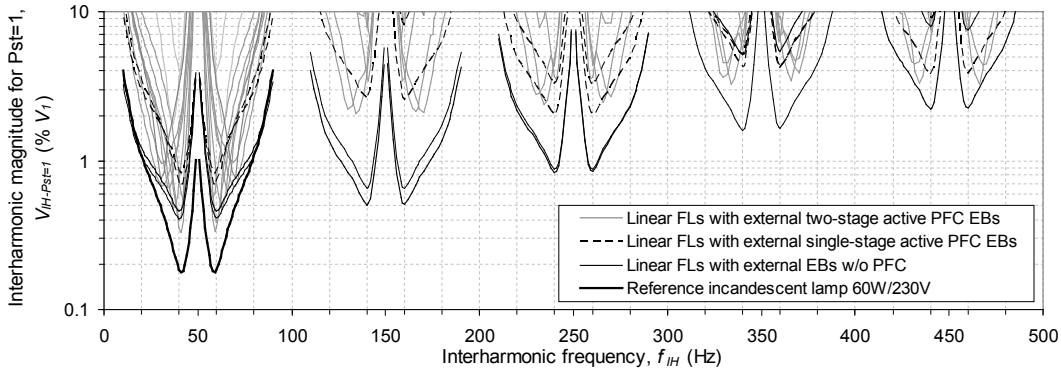


Figure A.5—Interharmonic-flicker curves of linear fluorescent lamps operated with external electronic ballasts of different designs

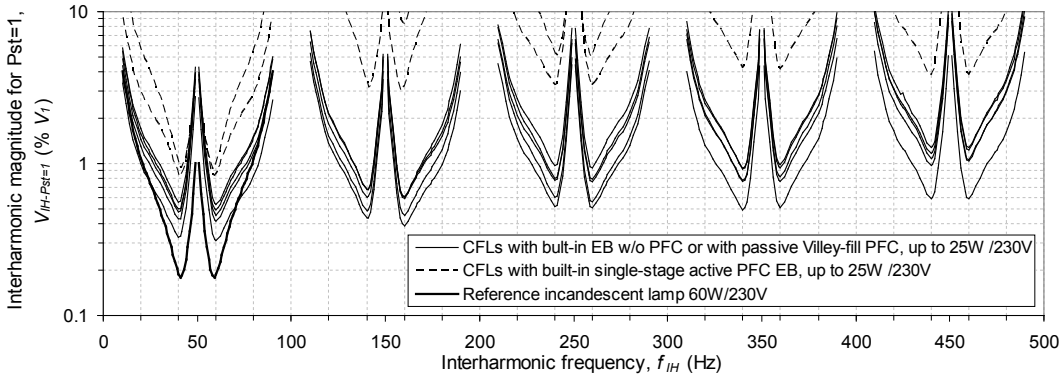


Figure A.6—Interharmonic-flicker curves of compact fluorescent lamps with built-in electronic ballasts (input power up to 25 W)

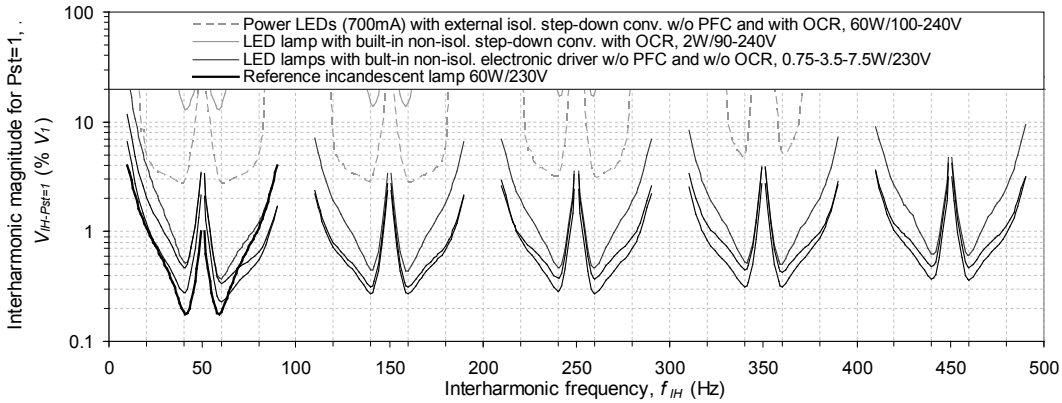


Figure A.7—Interharmonic-flicker curves of various LED lamps

A.4 IEC flickermeter response

With regards to the response of the IEC flickermeter to interharmonics below $2f_0$, it was demonstrated that in the presence of a couple of interharmonic components superimposed to the fundamental and producing AM, if a<<1 the instantaneous flicker sensation, P_{inst} can be approximated by the following equation (Cai, et al. [B18]):

$$P_{inst} \cong G^2 G_{f_M}^2 \, 2a^2 \tag{A.2}$$

where

$G = \sqrt{1238400}$ is a gain factor related to the normalization of the weighting curve

G_{fM} is the gain introduced to take into account block 3 filters.

Block 5 of the flickermeter performs a statistical analysis to obtain the P_{st} index. In this case, the P_{inst} is almost constant, this means that all the percentages are equal to this constant value and therefore:

$$P_{st} = 0.505 \times G \times G_{\Delta\omega} \times 2a \tag{A.3}$$

In the case of amplitude modulation, the P_{st} is proportional to the double of the interharmonic component amplitudes weighted according to their relative distance from the fundamental angular frequency.

On the other hand, when a single interharmonic of amplitude $2a$ is superimposed to the fundamental, if a<<1 the instantaneous flicker sensation, P_{inst} can be approximated by the following equation:

$$P_{inst} \cong G^2 G_{\Delta\omega}^2 4a^2 \tag{A.4}$$

Finally, Block 5 of the flickermeter gives:

$$P_{st} = 0.505 \times G \times G_{\Delta\omega} \times 2a \tag{A.5}$$

In the case of a single interharmonic component, the P_{st} is proportional to the amplitude of the interharmonic component weighted according to its relative distance from the fundamental angular frequency.

Comparing Equation (A.3) and Equation (A.5), it can be concluded that a single interharmonic component must have an amplitude equal to the double of two interharmonics causing amplitude modulation in order to produce the same P_{st} output of the IEC flickermeter.

Figure A.8 shows the amplitude of interharmonic components producing a unity P_{st} in the frequency range from almost 15 Hz to almost 49 Hz. The results were obtained by means of Equation (10), Equation (12), and by means of a numerical implementation of the IEC flickermeter. The accuracy of analytical formulas is very good from 22.5 Hz to 50 Hz, which is the range of maximum interest.

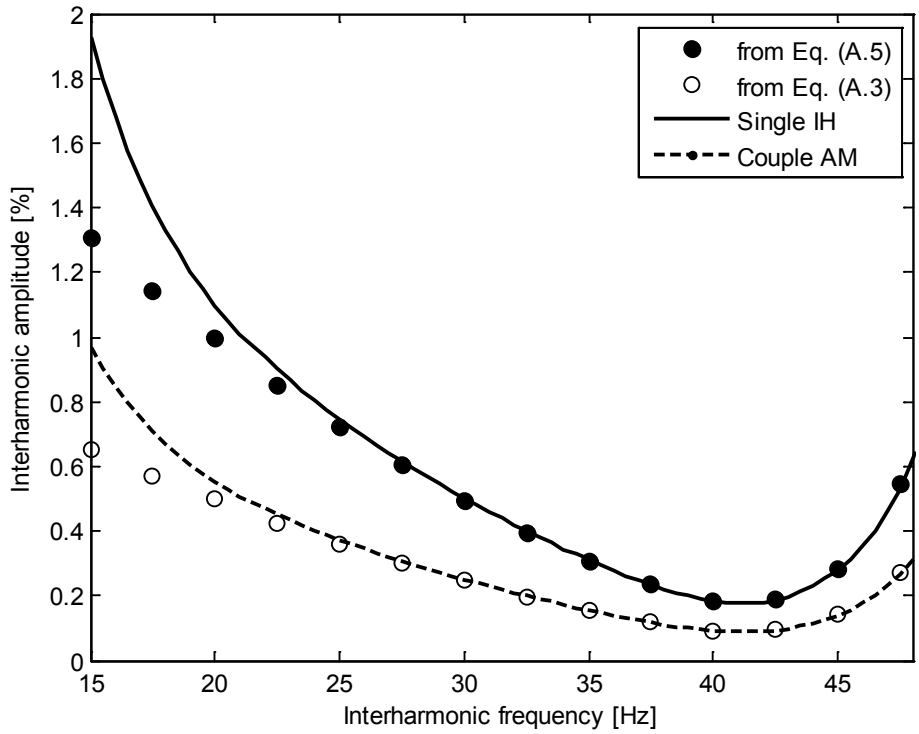


Figure A.8—Flickermeter response for two situations producing unity P_{st} in the instrument frequency band compared to the results obtained from the analytical formulas

Annex B

(informative)

Methods to compute flicker transfer coefficient

A flicker transfer coefficient between two bus bars in a network (e.g., A and B in Figure B.1) is defined as the ratio of the short-term flicker level at Bus B that is the direct result of the short-term flicker level at Bus A. This ratio is shown in Equation (B.1).

$$T_{PstAB} = \frac{P_{stB}}{P_{stA}} \tag{B.1}$$

where

T_{PstAB} is the transfer coefficient from bus A to bus B
P_{stB} is the short-term flicker level at Bus B
P_{stA} is the short-term flicker level at Bus A

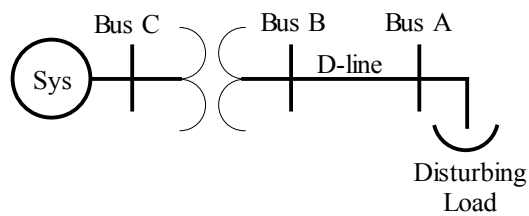


Figure B.1—Example radial system

It is important to recognize that the P_{st} values shown in Equation (B.1) do not correspond to any particular statistical values, but merely represent the two short-term flicker levels synchronously measured during a single 10 minute period. It is essential that the measurements correspond to the same time period and the measuring equipment is in conformity with IEC.

When synchronous flicker measurements are unavailable, T_{PstAB} can be estimated using the various frequency domain calculation methods that are provided in IEC 61000-3-7 [B25] and IEEE Std 1453.1-2012 [B35]. These methods are presented as follows.

Since P_{st} values are related to fluctuations in RMS voltage, Equation (B.1) can be shown to be equivalent to Equation (B.2) where ΔV is the change in voltage at a particular bus. This equation can be readily solved using traditional short-circuit calculation techniques.

$$T_{PstAB} = \frac{P_{stB}}{P_{stA}} = \frac{\left(\frac{\Delta V_B}{V_B}\right)_{RMS}}{\left(\frac{\Delta V_A}{V_A}\right)_{RMS}} \tag{B.2}$$

In the case of radial system such as the one shown in Figure B.1, flicker transfer coefficient can be computed using the short-circuit MVA at two uses using simplified equation in Equation (B.3).

$$T_{PstAB} = \frac{MVA_A}{MVA_B} \tag{B.3}$$

The method above is valid only for radial systems. In case of a networked system, the transfer coefficient from Bus A to Bus B can be determined by the following:

— Applying a three-phase fault at Bus A

— Computing the per-unit change in voltage at Bus B due to the applied fault at Bus A

Thus, assuming a pre-fault or pre-disturbance voltage at Bus A and B of 1.0 p.u., Equation (B.2) can be reduced to Equation (B.4).

$$T_{PstAB} = 1 - \overline{V}_{B3\varphi} \tag{B.4}$$

where

$\overline{V}_{B3\phi}$ is the complex voltage at Bus B due to a three-phase fault applied at Bus A (p.u.)

It should be noted that Equation (B.4) is only valid if the frequency dependence of system parameters can be ignored. In general, this can assumed to be true; however, it may not be if the bus in question is near a significant amount of generation, e.g., generating plant. In this situation, it may be necessary to model the synchronous machines in detail as opposed to using the traditional short-circuit model (sub-transient reactance). More information on this subject can be found in Tennakoon [B44].

Operation of arc furnaces naturally lead to rapid and significant real and reactive power variations that cause voltage fluctuations and the resulting flicker has the potential to propagate in power systems. The magnitude of the level of flicker that propagates depends on quite a few factors including the capacity of the arc furnace and its operation, configuration of the power system, fault level at the point of connection of the arc furnace, fault levels at various bus bars of interest in the power system, and the types of loads connected at these bus bars.

This subclause covers the concept of flicker propagation with the aid of three case studies. These studies are related to major ac arc furnaces that are supplied by dedicated HV feeders but are connected to a bus bar that supplies other feeders as well. The propagation of flicker is illustrated together with the concept of *flicker transfer coefficient* and its dependence on the type of load connected at bus bars where one is interested in knowing the level of flicker that propagates from an upstream bus bar. Particular emphasis is placed on the impact of directly connected asynchronous and synchronous machines as a type of load that has a significant influence on flicker attenuation.

With regard to assessment and compliance, the critical point for analyzing voltage perturbations and hence flicker is the PCC, where the network operator has to evaluate the conformity with the contractual parameters. These parameters are stipulated by documents such as IEC/TR 6100-3-7:2008 [B15] and EN 50160: 2010 [B6].

B.1 Case study 1

The power system configuration shown in Figure B.2 represents a network that can be used to analyze and examine the flicker propagation throughout the network (Tennakoon [B38]). The transformer T1 is supplied by the 400 kV system and is dedicated to the 60 MVA arc furnace installation. The transformer T2 is connected to the 400 kV bus bar and supplies other loads at various intermediate voltage levels.

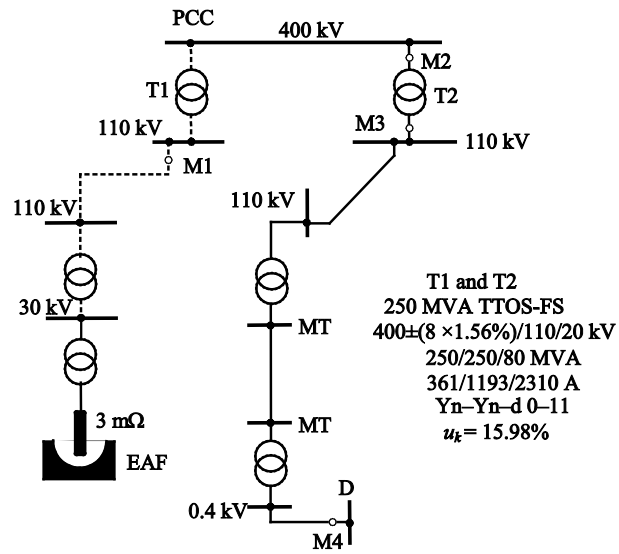


Figure B.2—AC arc furnace supply system and the surrounding power system

A synchronized flicker measurement exercise was carried out at bus bars *M1*, *M3*, and *M4* using the power quality monitoring analyzers configured using the same laptop and by setting automatic data logging commencement time to be the same (for example, all measurements started at 1 p.m.). The duration of measurement campaign was 14 consecutive days, comprising operating and down periods of the ac arc furnace. During the data logging, the power quality analyzers were dependent on their internal clocks and some drift in time could naturally take place but considering parameters such as P_{st} and P_{lt}, which are characterized by long computational windows, a drift in time by say 20 s was not expected to cause major errors. The measurements were conducted in networks with the neutral grounded, and the flicker was measured line to neutral.

The purpose of the measurement exercise was to examine the flicker levels at the low-voltage level, and therefore to estimate the flicker transfer from high-voltage to low-voltage networks.

B.1.1 Short-term flicker index measurements

The variation of the short-term flicker index P_{st}, on phase *A*, at bus bar *M1* is illustrated in Figure B.3 while the corresponding cumulative probability function is illustrated in Figure B.3 yielding a 95% value of P_{st} as 10.59.

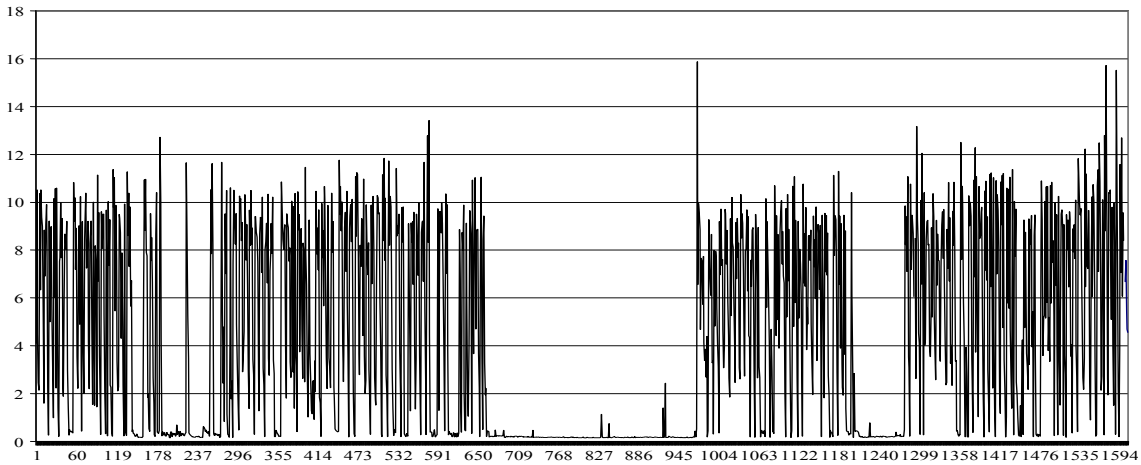


Figure B.3—Variation of P_{st} values on phase *A*, recorded at bus bar *M1*

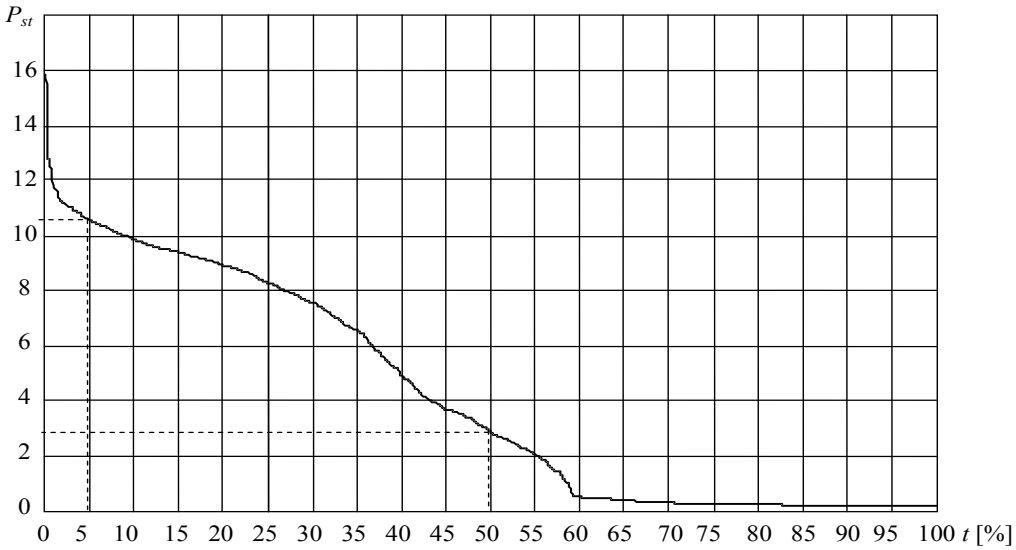


Figure B.4—Cumulative probability function of P_{st} at bus bar *M1*, on phase *A*

The variation of P_{st}, on phase *A,* at bus bar *M3* is shown in Figure B.5, while the cumulative probability function is illustrated in Figure B.6 and the corresponding 95% value of P_{st} is 1.49.

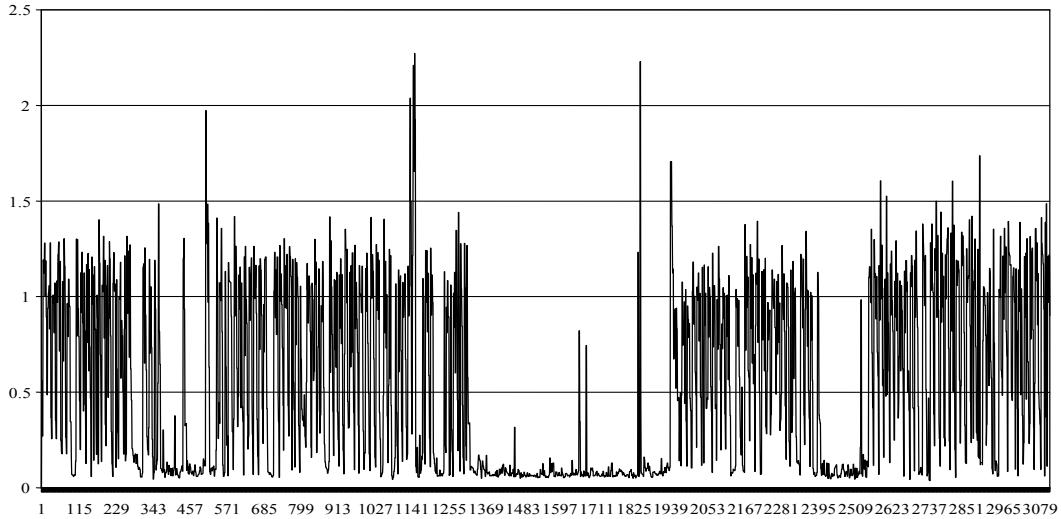


Figure B.5—Variation of P_{st} values on phase *A*, recorded at bus bar *M3*

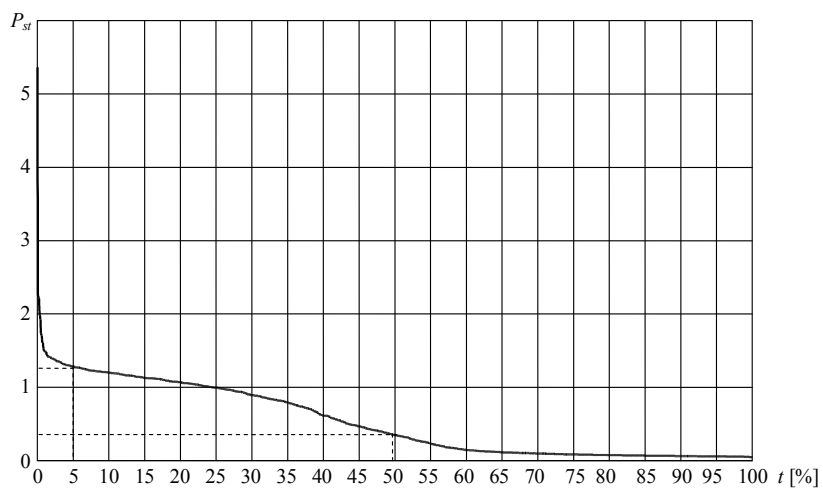


Figure B.6—Cumulative probability function of P_{st} at bus bar *M3*, on phase *A*

The variation of the P_{st} values on phase *A* at bus bar *M4* are shown in Figure B.7, while the corresponding cumulative probability function is illustrated in Figure B.8, which gives a 95% value of P_{st} as 1.33.

Comparing 95% P_{st} value from Figure B.6 (bus bar *M3*) with that from Figure B.8 (bus bar *M4*), it can be noted that the flicker at bus bar *M3* (high voltage) has propagated to bus bar *M4* (low voltage) with only little attenuation.

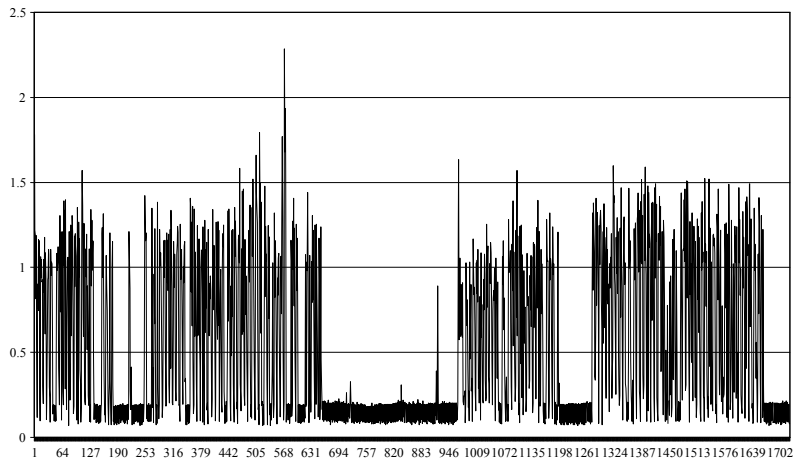


Figure B.7—Variation of P_{st} values on phase *A*, recorded at bus bar *M4*

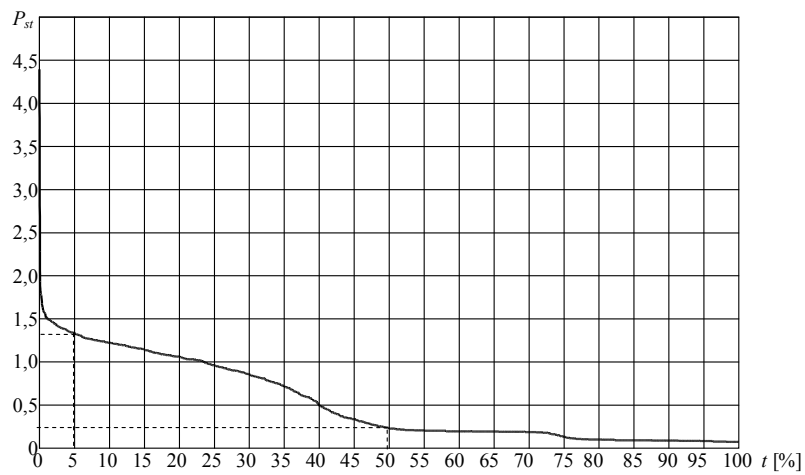


Figure B.8—Cumulative probability function of P_{st}, at bus bar *M4*

B.1.2 Long-term flicker index measurements

The variation of the long-term flicker index P_{lt}, on phase *A*, at point *M1* is illustrated in Figure B.9, while its cumulative probability function is illustrated in Figure B.10 and the corresponding 95% value of P_{lt} is 8.68.

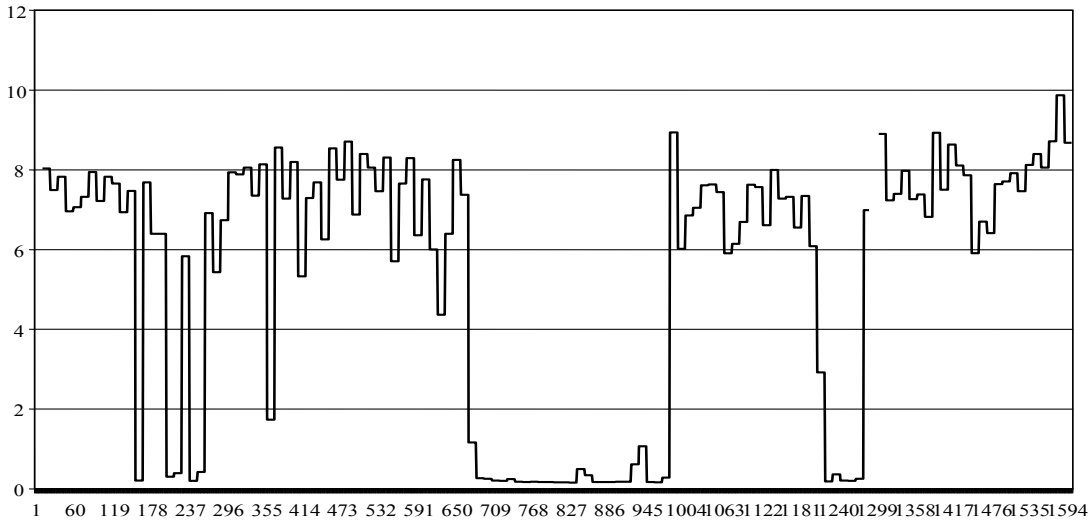


Figure B.9—Variation of P_{lt} values on phase *A*, recorded at bus bar *M1*

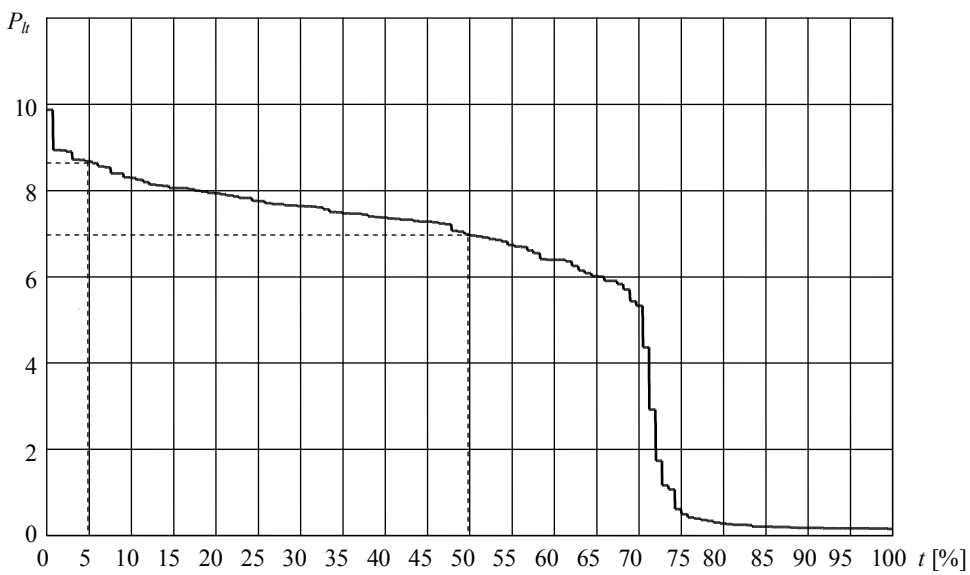


Figure B.10—Cumulative probability function of P_{lt} at bus bar *M1*, on phase *A*

The variation of the long-term flicker index P_{lt}, on phase *A*, at bus bar *M3* is illustrated in Figure B.11, while the cumulative probability function is illustrated in Figure B.12 and the corresponding 95% value of P_{lt} is 1.21.

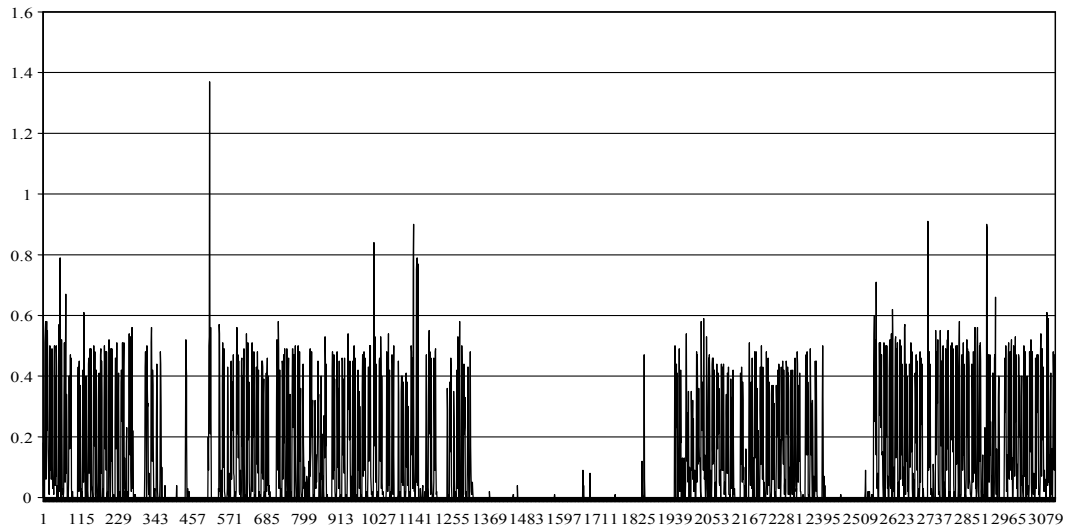


Figure B.11—Variation of P_{lt} values on phase *A*, recorded at measuring point *M3*

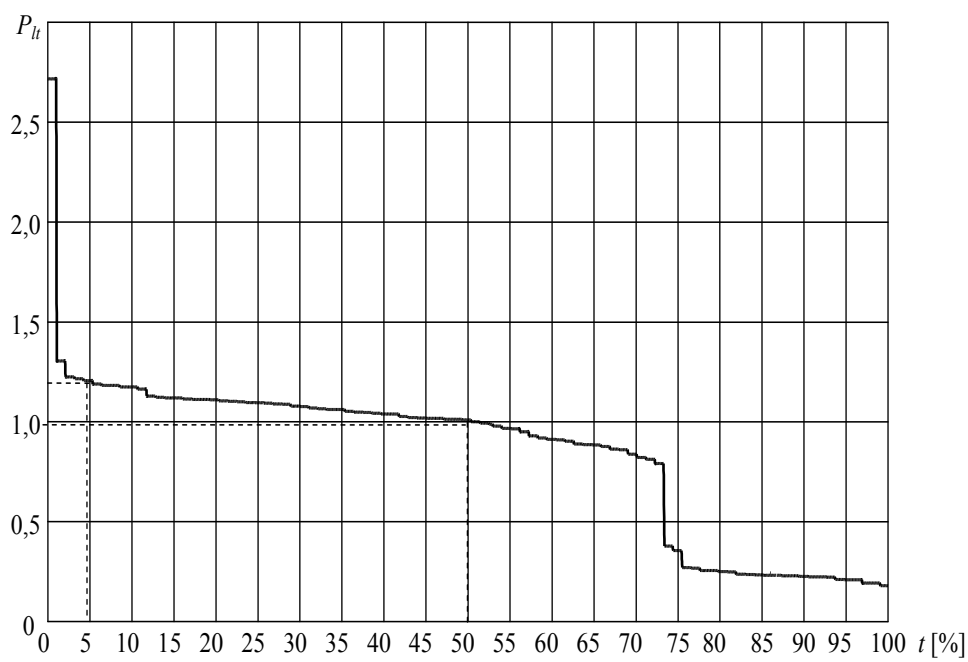


Figure B.12—Cumulative probability function of P_{lt} at *M3*, on phase *A*

The variation of the long-term flicker index P_{lt}, on phase *A*, at bus bar *M4* is illustrated in Figure B.13, while the cumulative probability function is illustrated in Figure B.14, which gives 95% value of P_{lt} as 1.1.

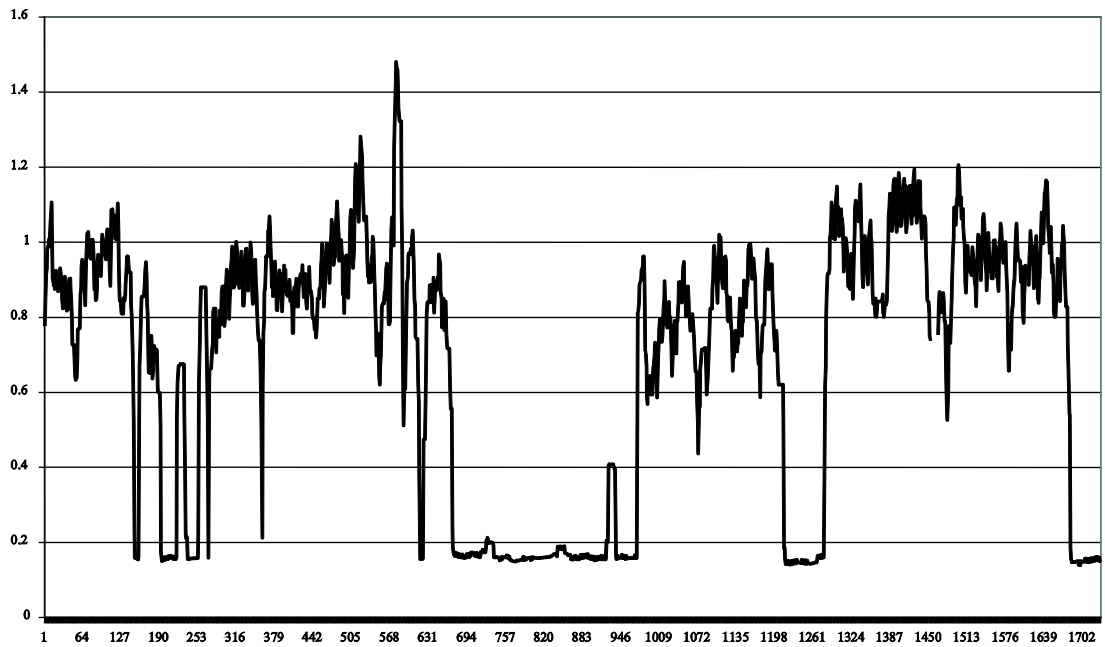


Figure B.13—Variation of P_{lt} values on phase *A*, recorded at bus bar *M4*

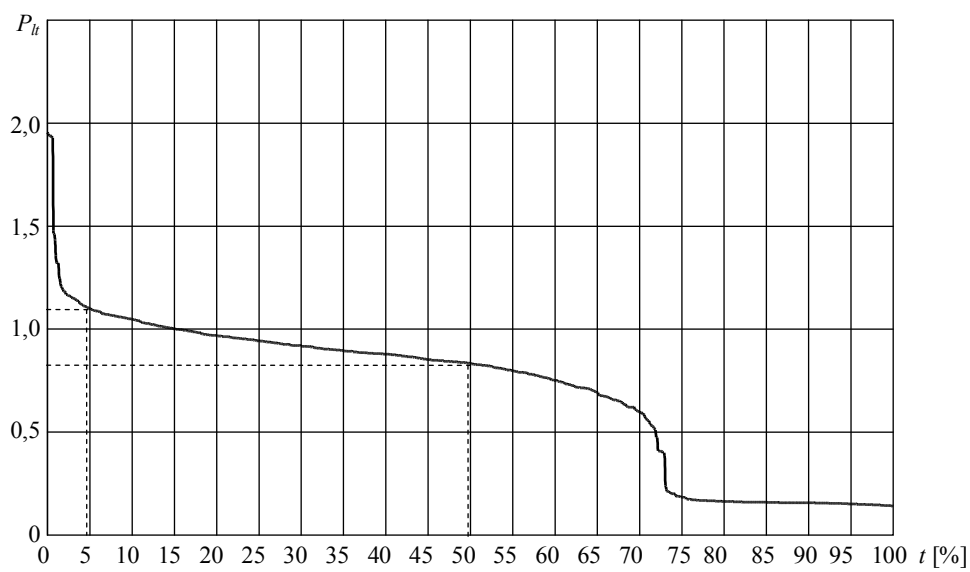


Figure B.14—Cumulative probability function of P_{lt} at bus bar *M4*

B.1.3 Flicker index measurement results

The flicker measurement exercise at low voltage level (400 V) highlights that the corresponding flicker levels have exceeded the recommended planning limits as given in IEC 61000-3-7. The 95% P_{st} and P_{lt} flicker indices corresponding to bus bars *M1*, *M3*, and *M4* of the network of Figure B.2 are listed in Table B.1.

Table B.1—Measured voltage flicker values for the network

	P_{st} (95%)	P_{lt} (95%)
M1	10.59	8.68
M3	1.49	1.21
M4	1.33	1.1

B.1.4 Analytical determination of flicker level at bus bars *M1* and *M2*

The analytical determination of flicker level was carried out using the following data referring to Figure B.2 and Figure B.15.

— Short-circuit power at 400 kV bus bar (M2) = S_{sc}≅6000 MVA

— Rated power of the 400 kV/110 kV transformer S_{T1}=250 MVA

— Short-circuit voltage 400 kV/110 kV transformer u_{sc1}=15.98%

— Line reactance x_l = 0.3 Ω/km

— Line length l = 5 km

— Rated power of the transformer 110 kV/30kV S_{T2}=160 MVA

— Short-circuit voltage of the transformer 110 kV/30 kV u_{sc2}=10%

— Rated power of arc furnace transformer 30 kV/0.6 kV S_{T3}=120 MVA

— Short-circuit voltage of arc furnace transformer, u_{sc3}=10%

— Reactance of the short network (the connection between furnace transformer and the arc furnace electrodes) X_{RS} = 3 mΩ

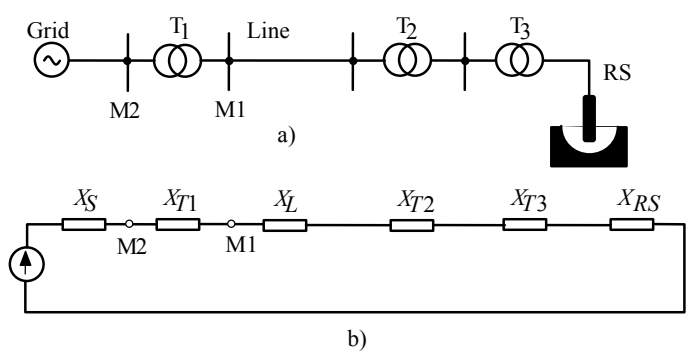


Figure B.15—The arc furnace supply system a) singe phase layout, and b) the equivalent network

The theoretical analysis estimates the voltage fluctuations on the 110 kV bus bar. For this purpose, the network referred to 110 kV is shown in Figure B.15 b).

With the parameters corresponding to the network in Figure B.15 b), the reactances of the equivalent scheme are as shown in Equation (B.5):

$$
\begin{aligned}
X_S &= \frac{cU_r^2}{S_{sc}} = \frac{1.1\times(110)^2}{6000} = 2.21\,\Omega\,; \\
X_{T1} &= \frac{u_{sc}}{100}\times\frac{U_r^2}{S_T} = \frac{15.98}{100}\times\frac{110^2}{250} = 7.73\ \ \Omega\,; \\
X_L &= 0.3\times 5 = 1.5\,\Omega\,; \\
X_{T2} &= \frac{u_{sc}}{100}\times\frac{U_r^2}{S_T} = \frac{10}{100}\times\frac{110^2}{160} = 7.56\ \ \Omega\,; \\
X_{T3} &= \frac{u_{sc}}{100}\times\frac{U_r^2}{S_T} = \frac{10}{100}\times\frac{110^2}{120} = 10.08\ \ \Omega\,; \\
X_{RS} &= 0.003\times\frac{110^2}{0.625^2} = 92.93\,\Omega\,.
\end{aligned}
\tag{B.5}
$$

Assuming that the voltage fluctuations at the various bus bars take place due to transition from the arc furnace open circuit condition to short-circuit condition, the voltage at bus bars M1 and M2 can be calculated as shown in Equation (B.6):

$$
\begin{aligned}
U_{M1} &= 63.5\times\frac{1.5+7.56+10.08+92.93}{2.21+7.73+1.5+7.56+10.08+92.93} = 58.33\ \text{kV} \\
U_{M2} &= 63.5\times\frac{7.73+1.5+7.56+10.08+92.93}{2.21+7.73+1.5+7.56+10.08+92.93} = 62.35\ \text{kV}
\end{aligned}
\tag{B.6}
$$

At bus bar M1, a voltage variation of about 8% is obtained, while at the 400 kV busbar, the voltage variation is about 1.5%.

The short-term flicker value can be determined, considering simplified hypothesis, using Lange [B25].

$$
P_{st} = \left(\frac{d}{d_{Pst=1}}\right)\times F \tag{B.7}
$$

where

d is the maximum voltage variation at the analyzed point
$d_{Pst=1}$ —the value corresponding to the curve
F— the shape factor of voltage variation

Based on the observation, there were 30 short-circuit occurrences per minute taking place in the arc furnace (corresponding to 60 voltage variations assuming they are to be of the rectangular type voltage variations), based on the P_{st} =1.0 curve, in IEC 61000-3-7, an admissible value of voltage variation (ΔV/V) of 0.8% is obtained.

Using a shape factor F = 1, the values of short term flicker, analyzed at bus bars 1 and 2 are as shown in Equation (B.8).

$$P_{stM1} = \left(\frac{\frac{63.5 - 58.33}{63.5} \times 100}{0.8} \right) \times 1 = 10.18$$

$$P_{stM2} = \left(\frac{\frac{63.5 - 62.35}{63.5} \times 100}{0.8} \right) \times 1 = 2.26 \qquad \text{(B.8)}$$

From the analytical computations of the short-term flicker, the calculated flicker value P_{st} = 10.18 is seen to be in close agreement with what has been measured for bus bar M1.

B.2 Case study 2

Figure B.16 shows a part of a large power system which supplies a 70 MVA ac arc furnace through a dedicated feeder connected to the upstream 132 kV bus bar A (classified as HV). This bus bar is also connected to other 132 kV feeders that supply major load bus bars E and F that are classified as residential and industrial respectively at 11 kV (MV) at downstream through 132 kV/11 kV step down transformers [although not shown, further 11 kV feeders emanate from these bus bars that supply customers at both 11 kV (essentially commercial and industrial) and 400 V (residential, commercial and industrial)].

A synchronized flicker measurement campaign (Tennakoon, et al. [B45]) was carried out on this network to examine how much of the flicker that is caused by the arc furnace propagates to the various bus bars. The results for buses A−F clearly demonstrates that propagation of the arc furnace flicker to upstream bus bars depend on the fault levels at the locations of interest whereas flicker propagation from a upstream to downstream bus bars depend essentially on the load composition.

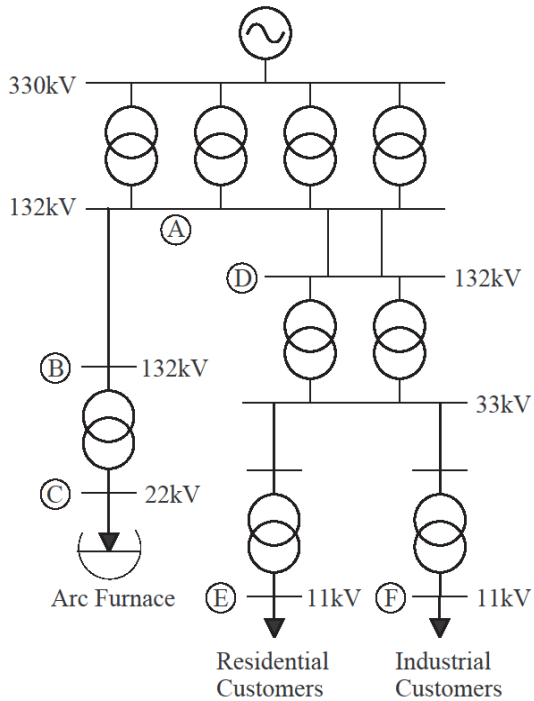


Figure B.16—Study system with an ac arc furnace (Tennakoon, et al. [B45])

The consistent transfer of flicker levels from bus bar C (22 kV) to bus bar B (132 kV) is evident from the correlation plots in Figure B.17 where the flicker levels on bus bar B (y-axis values) are compared against those at bus bar C (x-axis values). Slope of the correlation lines that is approximately equal to 0.18 can be noted to be equal to the ratio of the fault levels at bus bars C and B.

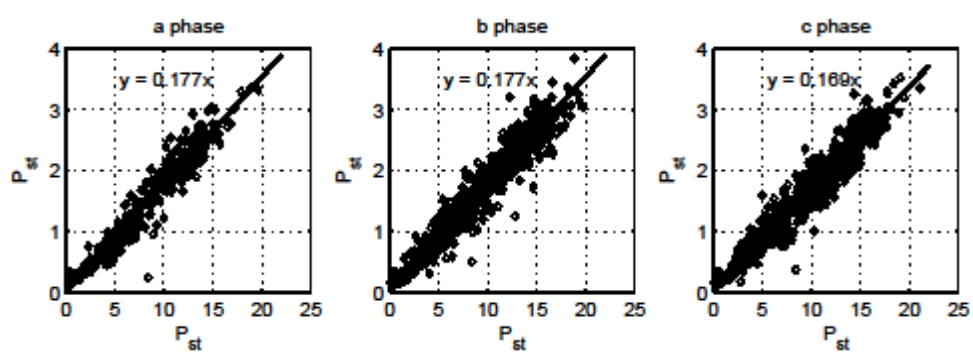


Figure B.17—Flicker transfer from bus bar C to bus bar B (Tennakoon, et al. [B43])

Flicker transfer from bus bar B to bus bar A as illustrated in Figure B.18 also demonstrates that downstream to upstream flicker attenuation is governed by ratio of fault levels at the two bus bars.

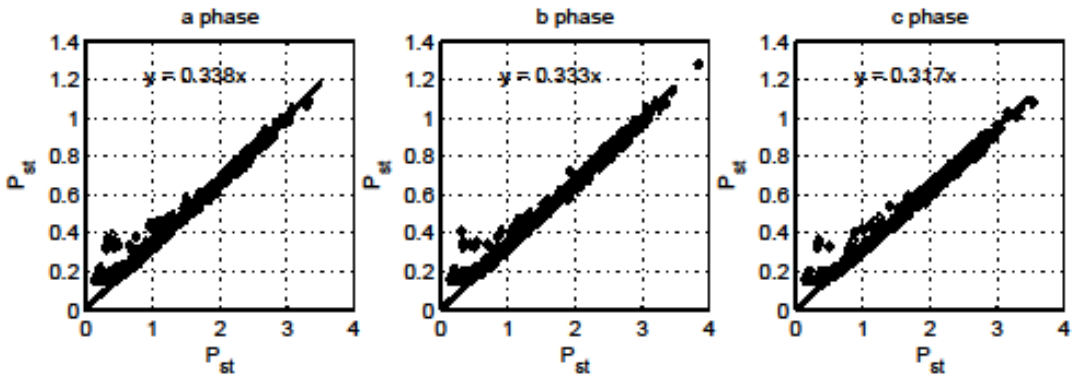
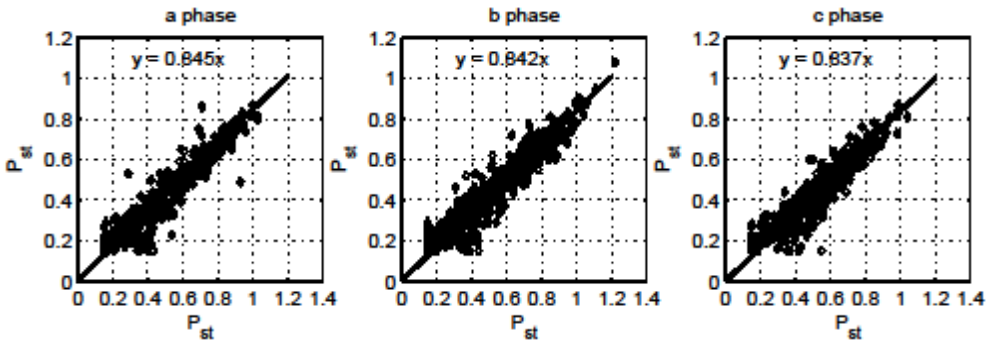
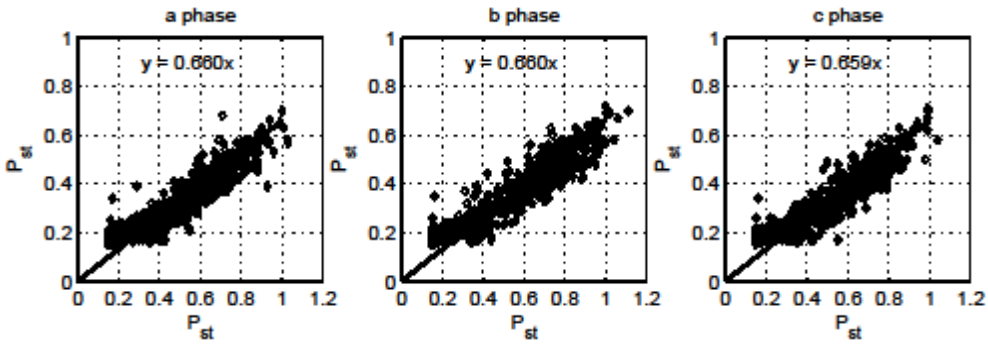


Figure B.18—Flicker transfer from bus bar B to A (Tennakoon, et al. [B43])

As can be seen from Figure B.16, bus bar D is common to bus bars E and F where bus bar E primarily supplies residential loads whereas bus bar F supplies industrial loads. Figure B.19 a) and b) illustrate the flicker transfer behavior from this upstream bus bar to the two downstream bus bars E and F respectively.



a)



b)

Figure B.19—Flicker transfer from bus bar D to bus bars E and F (Tennakoon, et al. [B43])

The slopes of the regression lines (~0.84 against ~0.66) clearly indicate that the industrial bus bar helps attenuate the upstream flicker relatively more effectively compared to the residential bus bar, a feature that can be attributed to the heavy population of mains connected induction motors that are supplied by bus bar

F compared to the more passive type of loads that would be supplied by bus bar E. These slopes can also be interpreted as upstream to downstream flicker transfer coefficients (T_{Pst}) as defined in documents such as IEC 61000-3-7, which are used in the flicker emission allocation process.

B.3 Case study 3

Time synchronized flicker measurements were made for approximately two weeks at the locations shown in Figure B.20:

a) 115 kV PCC of the EAF (Bus 1)

b) 115 kV (Bus 2) and 12.47 kV buses at a nearby distribution substation (Bus 3)

c) 120 V bus of a residential customer fed from the subject distribution station (Bus 4) (Tennakoon, et al. [B44])

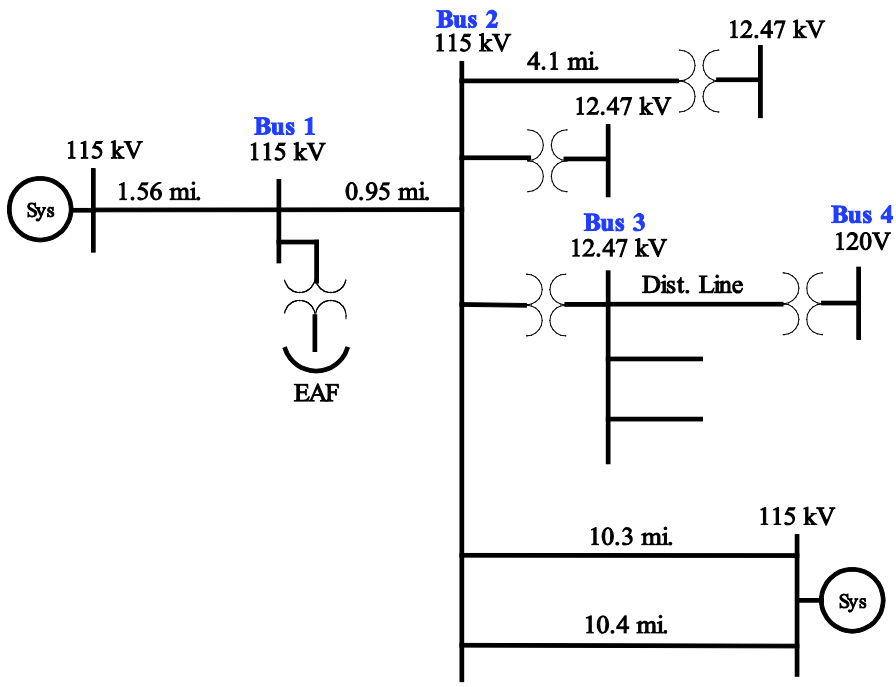


Figure B.20—One-line diagram of case study 3 (Tennakoon, et al. [B45])

Flicker measurement data at Bus 1 and Bus 2 are presented in Figure B.21. The flicker transfer coefficient was computed using linear regression and found to be equal to 0.866. The calculated flicker transfer coefficient assuming no load was found to be 0.89.

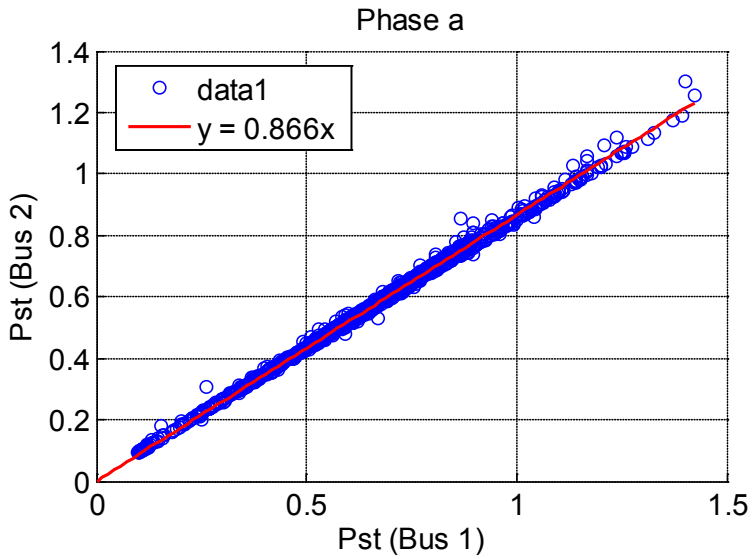


Figure B.21—Transfer coefficient from EAF PCC (Bus 1) to 115 kV bus at distribution substation (Bus 2) of system shown in Figure B.20

Flicker measurement data at Bus 2 and Bus 3 are presented in Figure B.22. The flicker transfer coefficient was computed using linear regression and found to be equal to 0.98. Because the distribution substation feeds primarily residential load, it was not surprising to find that the flicker transfer coefficient between the HV and MV bus was nearly unity. This is because residential load consist primarily of small single-phase motors and lighting that are connected through sizeable impedances (step-down transformers). As such, these loads have minimal effect on flicker transfer coefficients. Because of this, it is recommended to assume unity for HV to MV transfer coefficients.

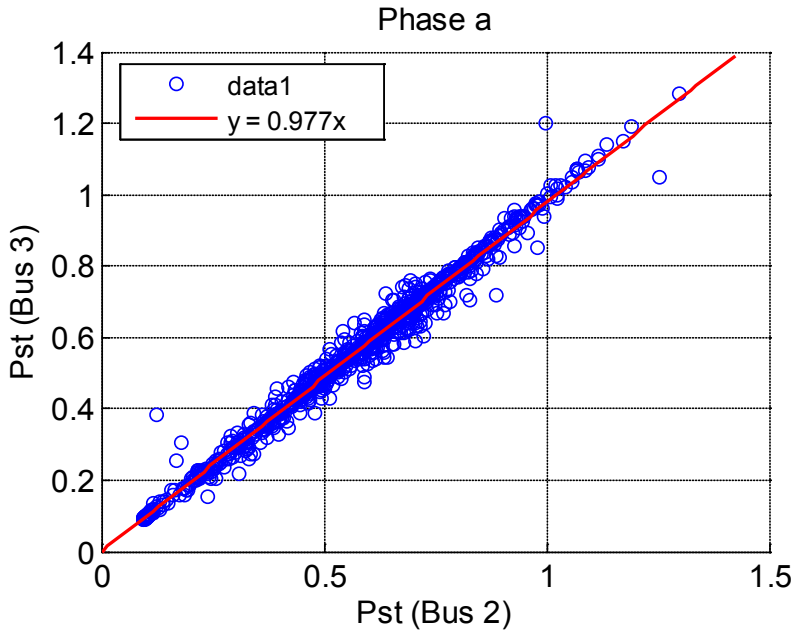


Figure B.22—Transfer coefficient from 115 kV bus (Bus 2) to 12.47 kV bus (Bus 3) at distribution substation of system shown in Figure B.20

Flicker measurement data at Bus 3 and Bus 4 (LV customer) are presented in Figure B.23.

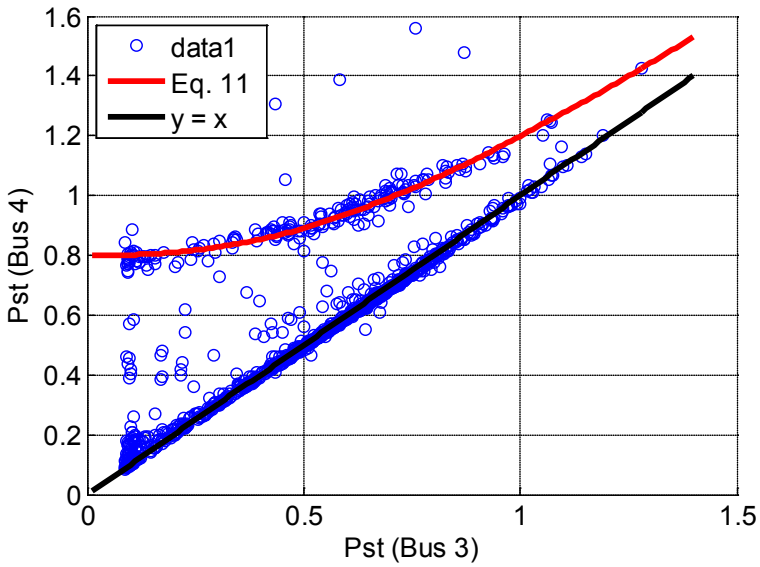


Figure B.23—Transfer coefficient from phase *a* of 12.47 kV bus (Bus 3) to 120 V bus at residential customer (Bus 4) shown in Figure B.20

The data plotted in Figure B.23 clearly shows that there are two distinct flicker transfer coefficients, and both are related to the global flicker level at LV. With the EAF off-line, the global contribution level (95th percentile) at LV was found to be approximately 0.80. When the flicker created by the EAF is coincident with that created at LV, the resulting LV flicker level can be characterized by Equation (B.9).

$$y = \sqrt[2.5]{(0.8)^{2.5} + (x)^{2.5}} \tag{B.9}$$

Equation (B.9) was derived using the summation law provided in IEC 61000-3-7. When the two flicker sources (residential load and EAF) are not coincident, the resulting flicker transfer coefficient from MV to LV is approximately unity. Equation (B.9) cannot be assumed to be valid in general; however, it does show that the summation of the two flicker levels (Global LV and that created by the EAF) can be higher than the cubic approximation that is widely used (Tennakoon, et al. [B44]).

B.3.1 Three-phase induction motors and flicker attenuation

The behavior exhibited by three-phase induction motors directly connected to the ac supply network (widely used in industry) has been examined both theoretically (Walker [B46] and IEEE Std 519 [B17]) and experimentally (Halpin, et al. [B10]) when they are subjected to regular voltage fluctuations. Although only sinusoidal modulation has been applied to the source supplying the induction motors, it has been noted that the complex dynamic behavior of three-phase induction motors depend on the modulation frequency and hence the effective dynamic impedance offered by the motor, which varies with the modulation frequency. Small scale laboratory experiment presented in Halpin, et al. [B10] clearly consolidates the idea that induction motors do help attenuate flicker compared to passive loads. Figure B.24 shows the outcomes of this work comparing the flicker transfer coefficients established for a radial network. The flicker attenuation for the scenario involving induction motor running at full load has been compared against the one involving equivalent passive load (similar to the real and reactive power requirements of the induction

motor running at full load). It is clearly evident that the passive load provides no flicker attenuation whereas the flicker attenuation provided by the induction motor has a modulation frequency dependency. It has to be accepted that many stationary and non-stationary frequency components exist in a fluctuating voltage caused by an arc furnace and hence the above results cannot be generalized, nevertheless is good evidence that supports the concept of significant flicker attenuation provided by induction motors.

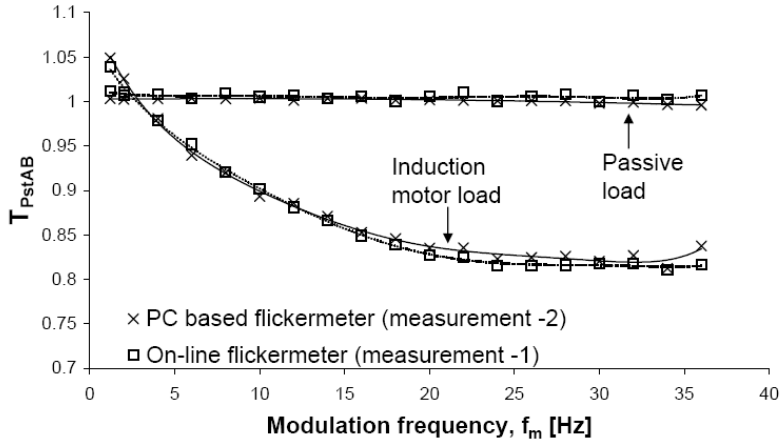


Figure B.24—Variation of flicker transfer coefficients with passive and induction motor loads

B.3.2 Large synchronous generators and flicker attenuation

Depending on the time frame of interest, traditional short-circuit modeling techniques utilize a simplified synchronous generator model whereby the machines are represented by their corresponding direct axis sub-transient or transient reactance. This method of modeling the machine is adequate for short-circuit calculations, and in some cases, harmonic simulations where the frequency response of the machine is required at integer harmonics. However, when the frequency response of a synchronous generator near 60 Hz is required, traditional machine models are no longer valid. To illustrate, the frequency response near 60 Hz of a 22 kV, 475 MVA synchronous generator was computed using the following three different machine models:

a) Sub-transient impedance

b) Transient impedance

c) Detailed machine model

The resulting frequency responses of the three models are provided in Figure B.25. As shown in Figure B.25, the frequency response of the detailed machine model diverges significantly from the simplified models. This effect is most noticeable in the 50–70 Hz range. In fact, at 60 Hz, the true machine impedance is approximately equal to its synchronous value. This suggests that when the frequency response of the machine near 60 Hz is required, e.g., flicker transfer coefficient calculations, modeling the machine by its direct axis sub-transient or transient reactance could introduce significant error depending on the flicker frequency and how closely coupled the bus of interest is to the synchronous generator. A procedure for computing flicker transfer coefficients near large synchronous generators is provided in Stanley [B39]. The method is also applicable to synchronous motors.

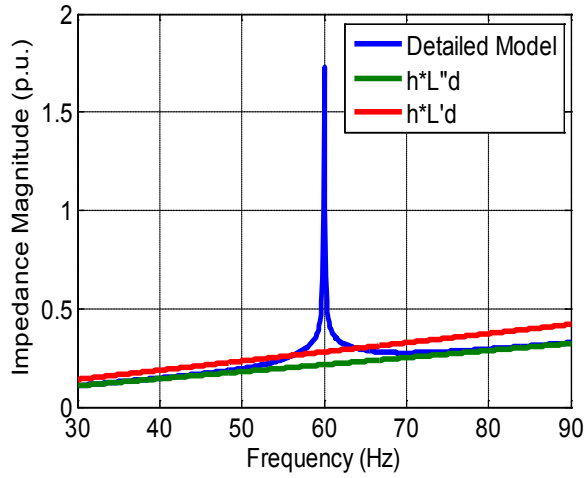


Figure B.25—Comparison of the detailed machine model, |r + jhX''d| and r + jhX'd versus frequency for a 22 kV 475 MVA 3600 RPM synchronous generator (Stanley [B39])

To illustrate the frequency dependence of flicker transfer coefficients consider the system shown in Figure B.26.

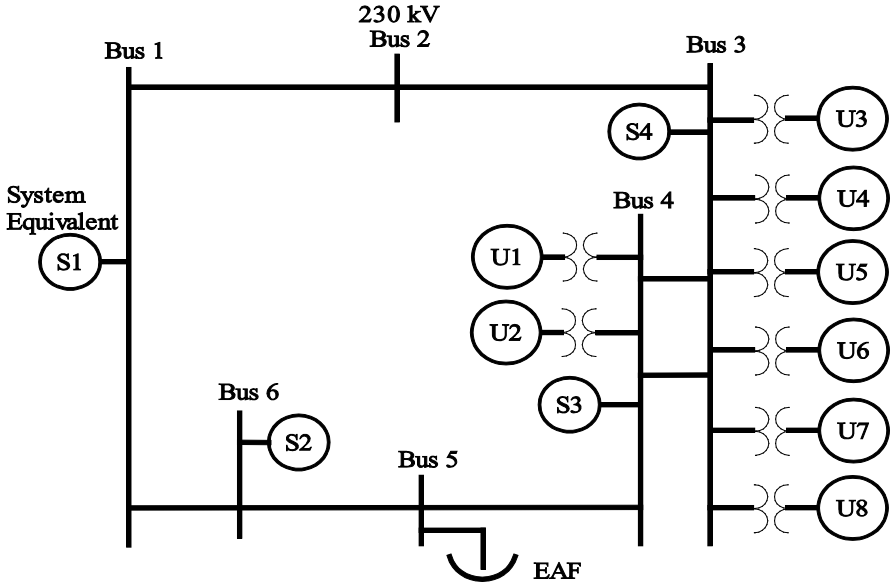


Figure B.26—Example system to illustrate the frequency dependence of flicker transfer coefficients

A large ac EAF (approximately 100 MVA) is located at bus 5. Bus 3 and bus 4 represent two buses at a nearby generating plant. The two transmission lines connecting buses 3 and 4 are very short, so for all practical purposes all of the generators are connected to the same bus. The combined MVA ratings of all 8 units is approximately 2735 MVA; thus, representing a significant source of synchronous generation. Using the procedure described in Stanley [B39], the flicker transfer coefficient between bus 5 and bus 4 was computed. The results of these calculations are provided in Figure B.27.

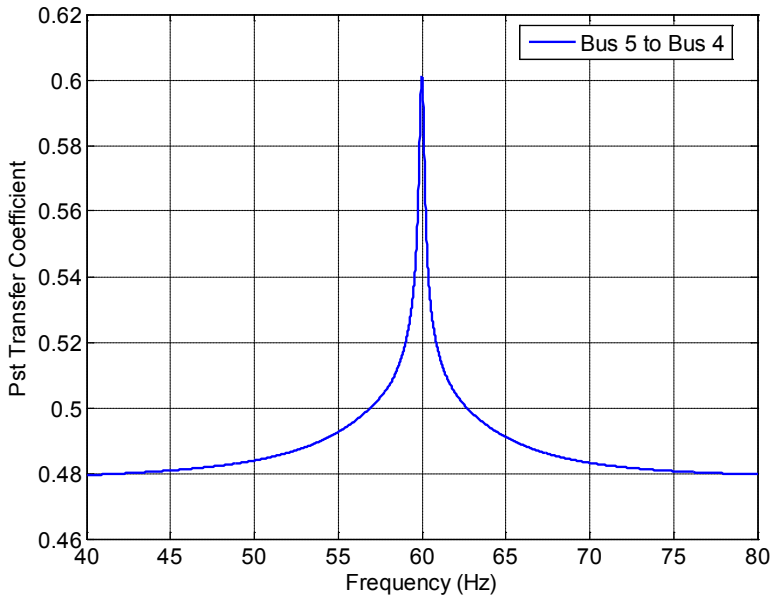


Figure B.27—Calculated flicker transfer coefficient between bus 5 and bus 4 of the example system depicted in Figure B.26

The calculation results presented in Figure B.27 indicate that the flicker transfer coefficient is indeed a function of the flicker frequency. The dominant flicker frequency of an ac EAF is typically in the range of 4−14 Hz, and; therefore, is used as a reference for determining the flicker transfer coefficient. Note that a flicker frequency range of 4−14 Hz corresponds to a frequency range of 46−56 Hz and 64−74 Hz in Figure B.27. Stanley [B39] suggests computing the flicker transfer coefficient at the bounding frequencies (e.g., 46 Hz and 56 Hz) and computing the average.

It is important to recognize that in many cases more sophisticated methods are not necessary. Field measurement data presented in Stanley [B37] suggests that in typical networked systems such as the one shown in Figure B.26, accurate results can be obtained with traditional short-circuit methods that utilize IEEE Std 519-1992 [B17].

Annex C

(informative)

Shape factors

The relationship between P_{st} = 1.0 curves for square-wave periodic changes and other periodic changes are tabulated in graphical form as shape factors in IEC 61000-3-7 and the same are reproduced here.

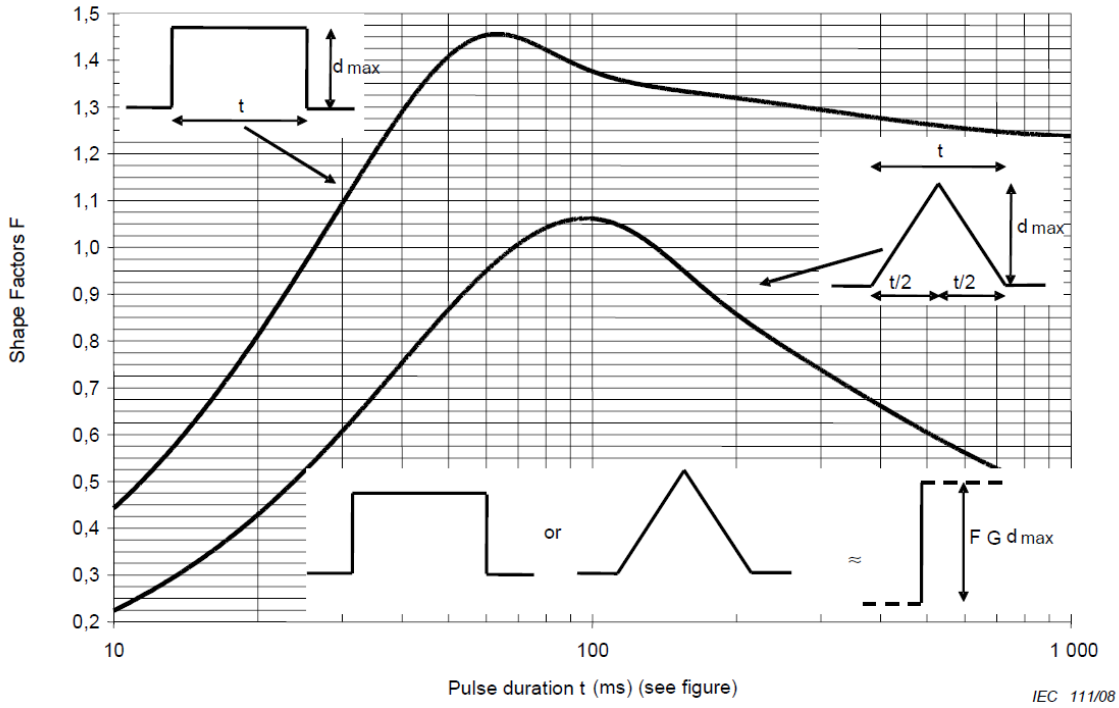


Figure C.1—Shape factor for pulse and ramp changes

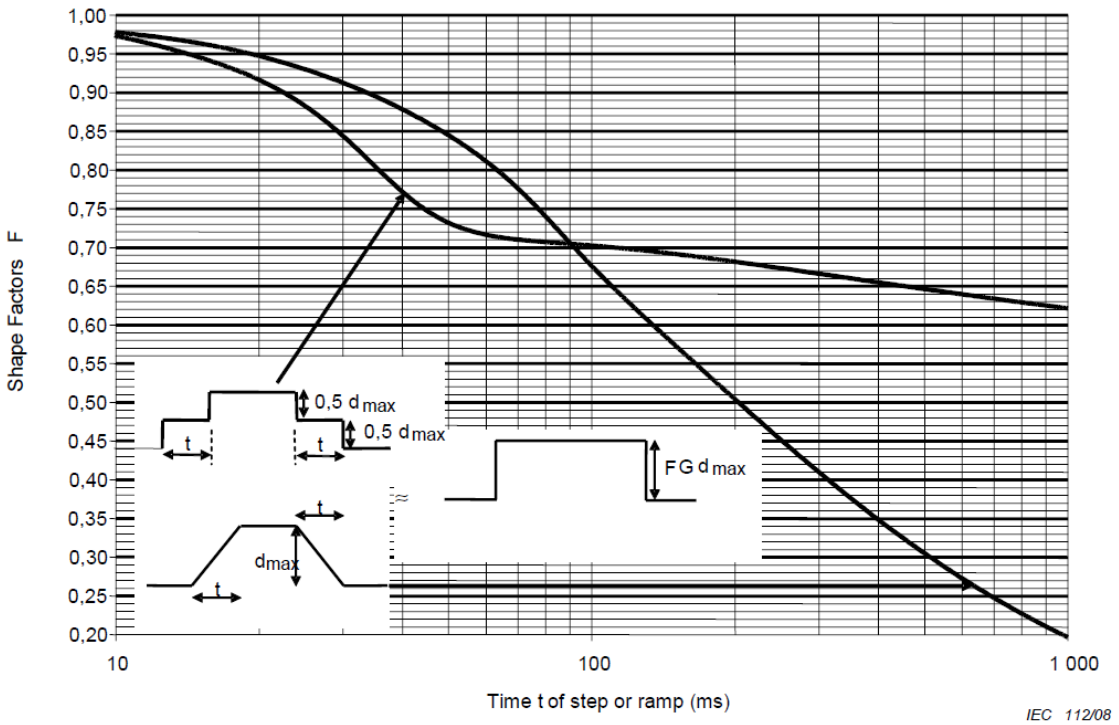


Figure C.2—Shape factor for double step and double ramp changes

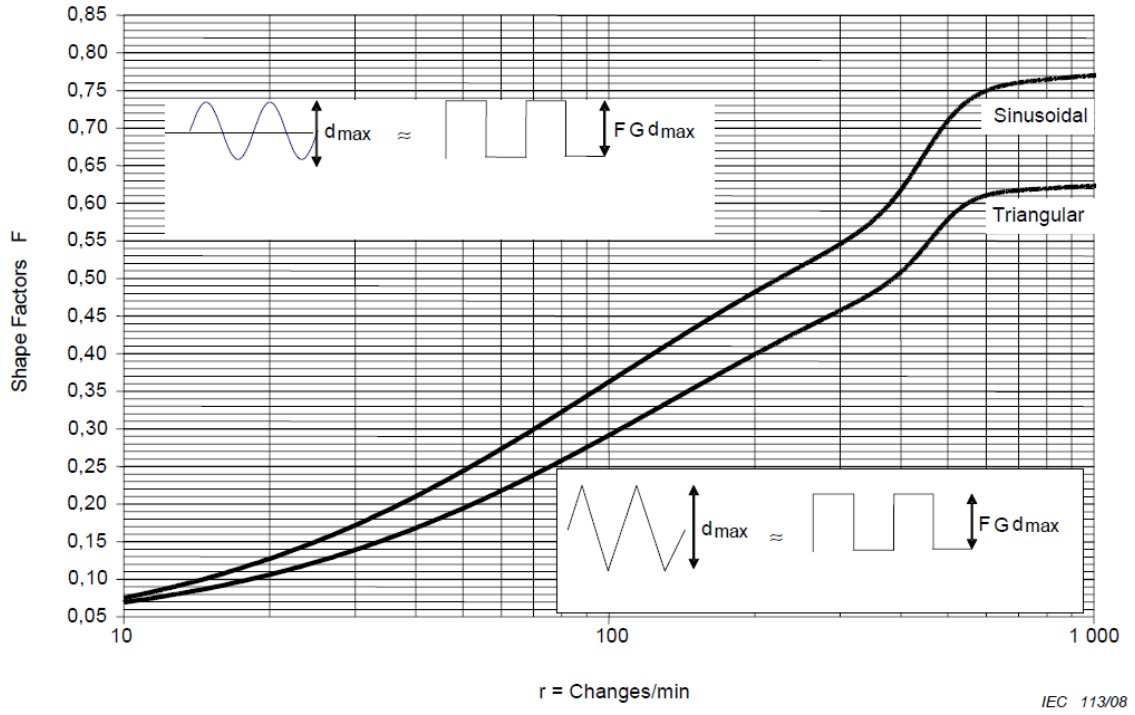


Figure C.3—Shape factor for sinusoidal and triangular changes

Annex D

(informative)

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