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Guidelines for Flicker Limits at Industrial Customers

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PRODUCT DESCRIPTION

Industrial customers can create problems for the electricity supply system when they have nonlinear loads or loads with significant variations that cause sudden voltage fluctuations, or flicker. Among the facilities that can have large variable loads are arc furnaces and other metal processing plants, plastics plants, cement plants, petrochemical operations, paper mills, chippers and rock crushers, and welders. Utilities are responsible for the quality of voltage supplied to customers, but they must make sure that the quality of the voltage is not adversely affected by the loads in these industrial facilities. Evaluating the effect of a particular customer on the voltage quality can be complicated, and recent developments in IEC (International Electrotechnical Commission) and IEEE (Institute of Electrical and Electronics Engineers) standards provide methods for measuring the disturbances and evaluating compliance with limits. This report presents guidelines and templates that utilities can use in applying flicker standards for industrial customers.

Results and Findings

This report makes recommendations for implementing the latest versions of the IEC and IEEE flicker standards, including:

- A flicker measurement method using a meter described by IEC and since adopted in IEEE Standard 1453
- Flicker limits for various voltage levels per IEC and IEEE recommendations
- Methodologies for identifying the flicker contributions of single customers
- Methodologies for estimating flicker levels at the point of common coupling
- A procedure for estimating flicker due to an electric arc furnace facility.

Challenges and Objectives

The electric utility industry needs to develop standard methods of evaluating and characterizing power quality concerns such as flicker, including the levels of flicker associated with industrial load installations. As standards organizations identify monitoring and evaluation methods and determine acceptable levels of power quality variations, utilities need to incorporate these recommendations into electric service contracts with industrial customers.

Applications, Values, and Use

The electric utility industry is starting to adopt IEEE Standard 1453 for evaluating flicker levels and has begun implementing limits for customers that cause voltage fluctuations. There is considerable value to the industry in developing consistent methods of applying flicker standards and establishing guidelines for evaluating compliance. Customers will benefit from consistent methods of evaluating compatibility with the utility supply system. Such methods will allow improved planning of facilities and support the design of solutions to deal with flicker issues.

EPRI Perspective

Industry standards on flicker are highly complex and require careful planning and application. By attempting to resolve some of the inherent ambiguities in current flicker standards, this report can help utilities develop the guidelines necessary to apply the standards consistently in a variety of situations. The report contributes to the ongoing effort to manage load variability, leveraging the extensive research in the area, including the work EPRI has performed on the subject over the years.

Approach

Input from EPRI's Flicker Interest Group on a number of key flicker issues and concerns helped establish the goals for this project. Through an in-depth analysis of international flicker standards and evolving methods of evaluation and application, the project team sought to build a single comprehensive reference on the subject, laying out consistent guidelines and methods and establishing a base for future updates as industry standards change.

Keywords

Arc furnace
Flickermeter
Flicker standards
Variable loads
Voltage flicker

ABSTRACT

This document provides the necessary background on flicker phenomenon that arises out of the fluctuations in power demands of large variable loads. Sensitivity curves are introduced that have been traditionally developed for incandescent lamps which show how voltage fluctuations can cause unacceptable variations in light output. A flicker measurement method is presented that has been standardized using a meter that is completely described in IEC Standard 61000-4-15 and since adopted in IEEE Standard 1453. The short-term (P_{st}) and long-term (P_{lt}) flicker indices that are used for the analysis of the flicker data are defined. The impact of interharmonics on flicker for various kinds of lamps and flickermeter is also addressed.

The flicker limits for various voltage levels as per IEC and IEEE recommendations are provided and the assessment procedure for evaluating flicker compliance against emission limits is described. The methodologies to deal with any background flicker to identify the flicker contribution of single customers are also presented.

The document also provides the methodologies for estimating flicker levels at the PCC (Point of Common Coupling) depending on the type of the load. The method of using shape factors and "Pst = 1" curve for estimating flicker due to known cyclic load profiles is presented. The procedure to estimate flicker due to an electric arc furnace facility is also presented. This estimate is a function of the system strength, furnace size and type, and is based on the actual measurements of flicker levels at arc furnace facilities all over the world. The time-domain simulation based approach for assessing flicker due to motor starting and arc furnace load has also been presented.

Finally, the document also includes example terms and language that can be the basis for defining relative responsibilities and assessment methods for customer installations that may cause flicker problems. Terms include limits, measurement methods, evaluation methods, and methods of improving performance.

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RECOMMENDATIONS FOR CHARACTERIZING FLICKER LEVELS

What is Flicker?

Voltage flicker can be defined as a sudden fluctuation in system voltage, which can result in observable changes in the light output of electric lamps. Because voltage flicker is mostly a problem when it is observed by the human eye, usually voltage flicker is referred to as a problem of perception. It can be an annoyance and hindrance to workplace productivity and peace of mind. Unlike most other PQ phenomena, voltage flicker seldom causes process interruptions or equipment damage.

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 [4]. A plot of the rms voltage magnitude vs. time such as Figure 1-1 can be used to illustrate the variations. The characteristic shown is due to the randomly changing arc characteristic as the scrap steel is melted in an arc furnace. The variations in rms voltage can be in the range of 0-3% of the nominal voltage.

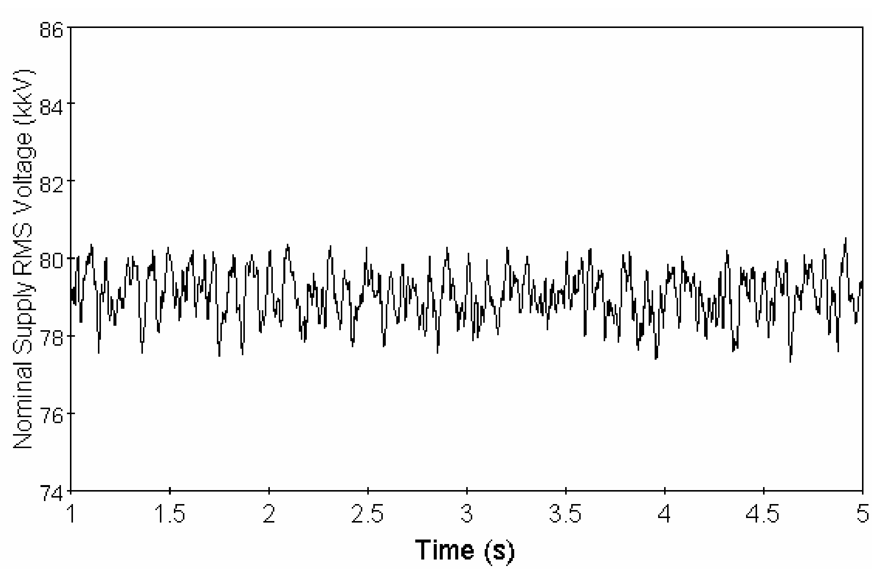


Figure 1-1.
Example of Voltage Fluctuations caused by an Arc Furnace Operation

The most important impact of these fluctuations is that they cause variations in the light output of various lighting sources. Since the beginning of last century, many companies developed curves to represent the severity of flicker through tests on human subjects. One such set of curves that were developed by GE and later modified and published by IEEE in Standard 141-1993/Standard 519-1992 are shown in Figure 1-2. 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 dips per sec. The curves were developed based on the standard (rectangular and sinusoidal) modulations of the 60-Hz sine wave. Such curves are suitable for step changes in rms voltages such as those encountered in motor starting 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 are unsuitability to handle complex voltage modulation due to use of adaptive var compensation for flicker control of seam welders and inability to address multiple dosage issues [5]. 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.

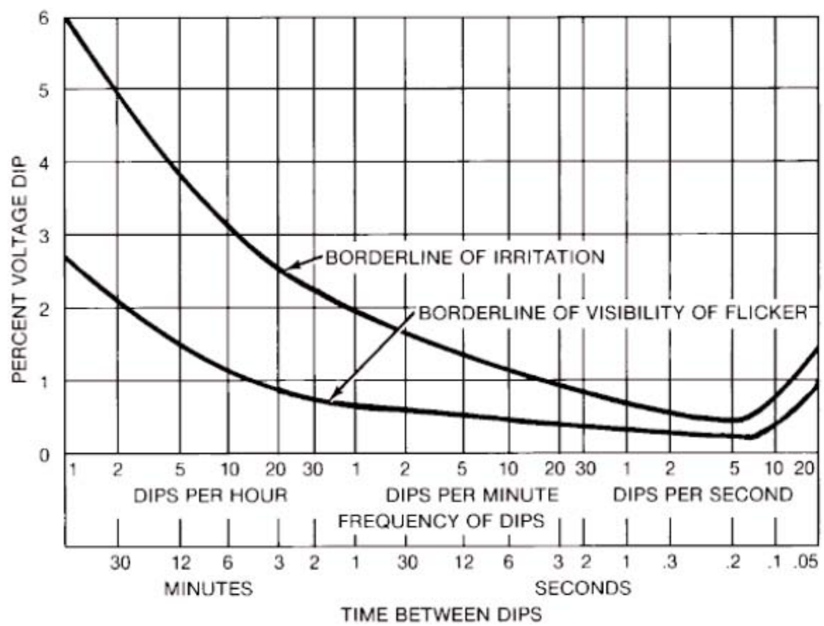


Figure 1-2.
Example of a Flicker Sensitivity Curve

IEEE Standard 1453 Flicker Monitoring Procedures

Flicker monitoring has been standardized in the United States using a meter that is completely described in IEEE Standard 1453. This method has been adopted from IEC Standard 61000-4-15. It may be noted that IEC Standard 61000-4-15 has replaced the well known IEC 868 flicker meter standard. This measurement method is based on years of combined research by engineers and scientists in the areas of the human ocular system, brain reaction and lamp response. Figure 1-3 is a block diagram of the flicker meter. The short description of individual blocks is given below:

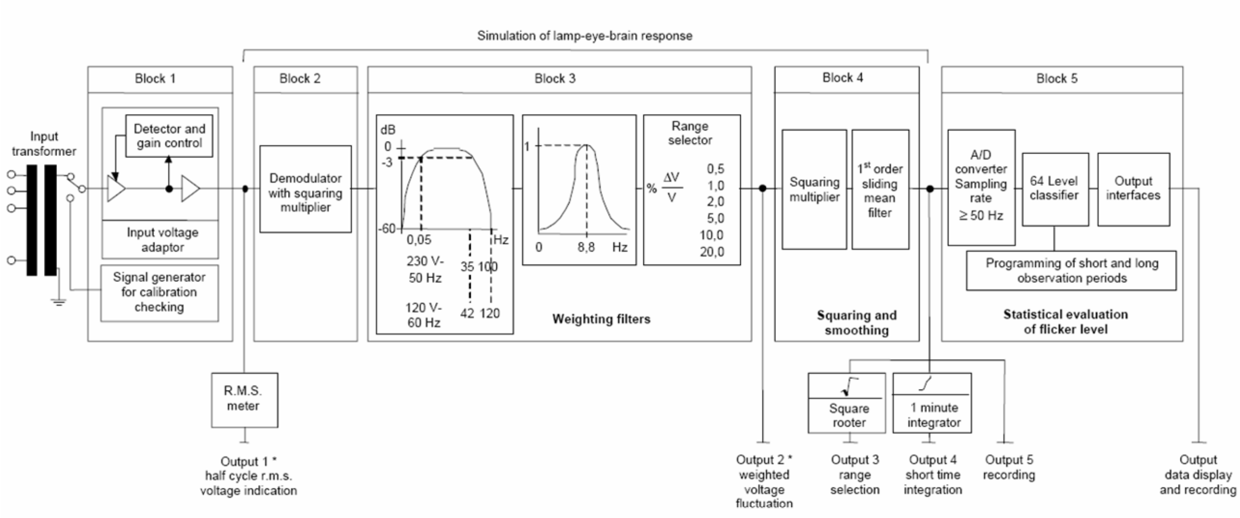


Figure 1-3.
Functional Block Diagram for the IEC Flicker Meter

Block 1 is an input voltage adapter which 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 which 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 which serve to filter out unwanted frequencies produced from 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 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 one 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 1-4 gives a graphical demonstration of both the probability density and cumulative distribution functions.

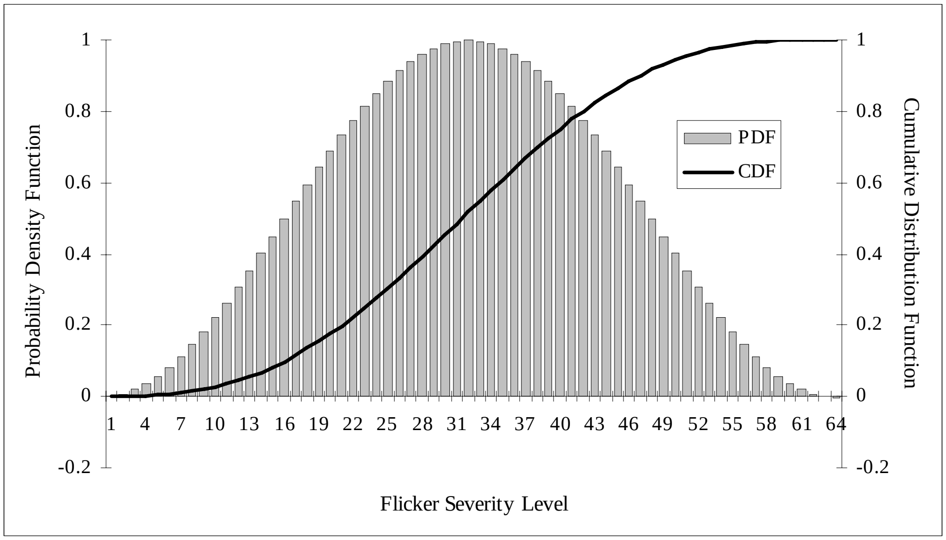


Figure 1-4.
Cumulative Distribution and Probability Density Curves

Flicker level evaluation can be divided into two categories, short-term and long-term. Short-term evaluation of flicker severity, Pst, is based upon an observation period of 10 minutes. This period is based upon assessing disturbances with a short duty-cycle or those which produce continuous fluctuations. Pst can be found using Eq. 1-1.

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \quad \textbf{Eq. 1-1}$$

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 discussed previously. The suffix 's' represents the smoothed value obtained using Eq. 1-2 through Eq. 1-5.

$$P_{1s} = \frac{P_{0.7} + P_1 + P_{1.5}}{3} \quad \textbf{Eq. 1-2}$$

$$P_{3s} = \frac{P_{2.2} + P_3 + P_4}{3} \quad \textbf{Eq. 1-3}$$

$$P_{10s} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \quad \textbf{Eq. 1-4}$$

$$P_{50s} = \frac{P_{30} + P_{50} + P_{80}}{3} \quad \textbf{Eq. 1-5}$$

The long term flicker severity, P_{lt}. is calculated from 12 successive P_{st} values using the equation in (6).

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} P_{st}^{3}}$$ **Eq. 1-6**

The original IEC standard was based on the effects of voltage fluctuations on a 60 Watt incandescent light on 230 volt systems. A 60 Watt incandescent light bulb designed for 120 volts is not as sensitive to the same voltage fluctuations because the filament is larger (longer time constant) to handle the higher current levels associated with the same Watt rating. As a result, an additional weighting curve was developed for 120 volt applications which are more common in North America. The 120 volt and 230 volt weighting curves are compared in Figure 1-5.

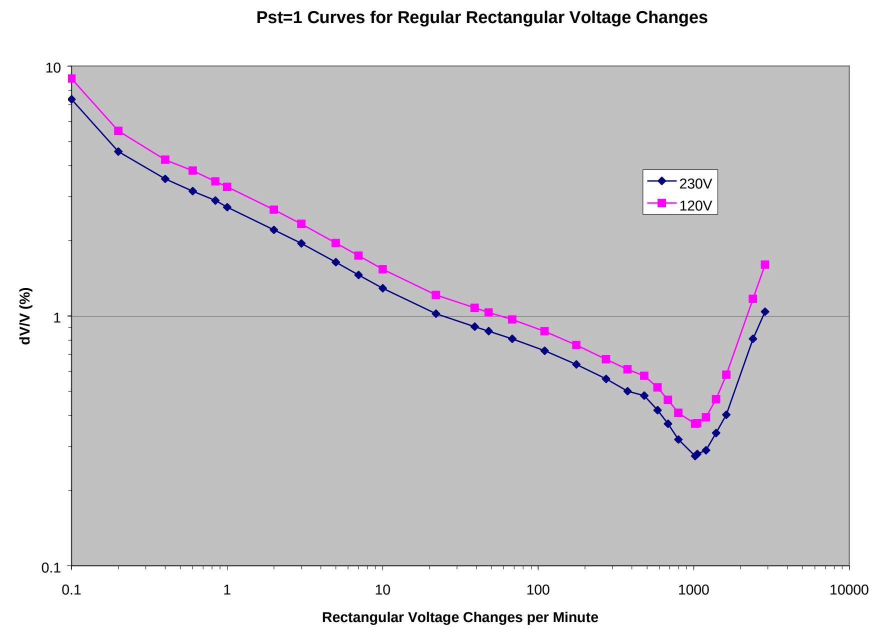


Figure 1-5.
Comparison of 120 volt and 230 volt Weighting Curves for Flickermeter Calculations

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 in power grids. Humans have 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 [6]. The lamps that were tested included:

- Two four-foot fluorescent fixtures with electronic ballasts (64 and 80 watts)
- Two CFLs with magnetic ballasts (13 and 15 watts)
- One 15-watt CFL with an electronic ballast
- One 45-watt halogen lamp
- One standard 60-watt incandescent bulb

The averaged test results for six human subjects are shown in Figure 1-6. It can be seen that with exception of a CFL with magnetic ballast, incandescent lamp is the most sensitive to flicker. This highlights the unsuitability of using standard IEC compliant flickermeter output for evaluating flicker performance of different lighting technologies.

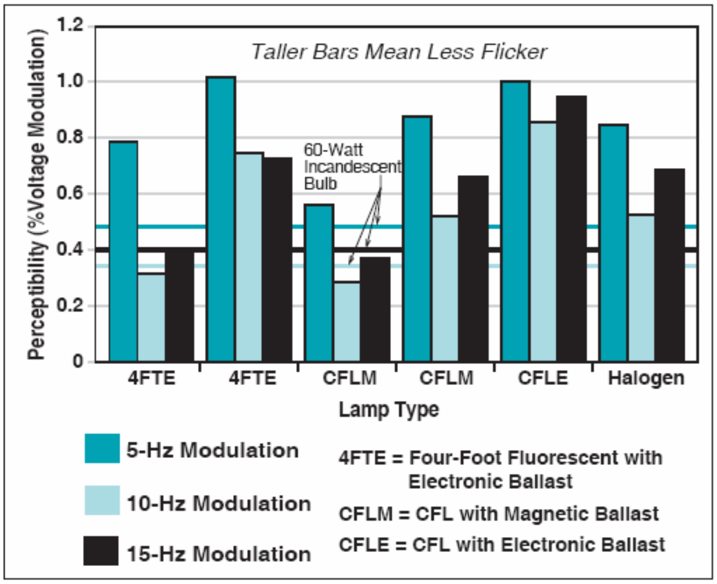


Figure 1-6.
Test results on Perception Thresholds of Humans [6]

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) to the percentage change in input voltage (Eq. 1-7).

$$GF = \frac{\left(\frac{\Delta\Phi}{\Phi}\right)}{\left(\frac{\Delta U}{U}\right)} \qquad \textbf{Eq. 1-7}$$

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 which is unique for each person. As a result, this approach allows comparison of lamp sensitivities in systematic and reproducible manner.

EPRI used this approach in computing the gain factors for different lamp types in mid 1990's [7]. Square wave modulation was used to simulate voltage variations at test frequencies of 10 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-watt incandescent lamp

The test results that included gain factor and perception were normalized based on incandescent lamps and are presented in Figure 1-7. It can be seen that there is a fairly good correlation between gain factor measurement and human perception of the flicker.

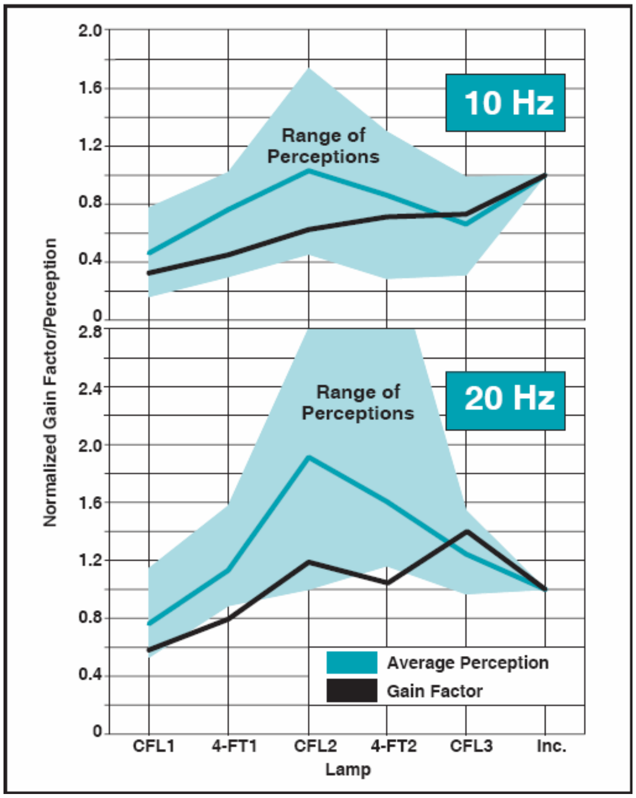


Figure 1-7.
Quantifying Flicker Performance of Lamps [7]

More tests [8] were carried out by EPRI on 1995-vintage lighting products that included the following:

- Twenty-three CFLs (3 samples each)
- Eleven four-feet fluorescent (3 samples each)
- 60 W, 120 V incandescent lamp

This testing encompassed a frequency range between 2 and 25 Hz and the plot of resultant gain factors is shown in Figure 1-8. It is evident that unlike for incandescent lamps, gain factor of fluorescent fixtures is independent of frequency. Also, the average gain factor of CFL is less than half in comparison to that of incandescent lamp at 8 Hz (most sensitive frequency for humans).

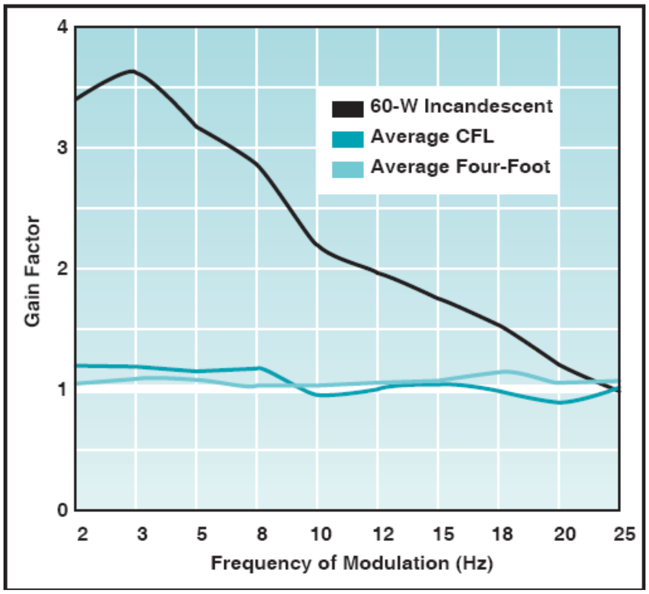


Figure 1-8.
Gain Factor Variation over the Test Frequency Range [8]

Based on the above findings, it can be concluded that different lighting technologies differ in flicker performance. IEC compliant flickermeter described earlier in the Chapter is designed and calibrated for incandescent lamps and is therefore not suitable for other lamp types. Authors in [9] 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. Despite their merits, such suggestions have not found their way into the industry standards as of now.

Impact of Interharmonics on Flicker

Superimposed interharmonics in power system can lead to oscillating luminous flux and thus become a source of light flicker [10]. This section summarizes the impact of interharmonics on the flicker and the performance of flickermeters

Impact of Interharmonics on Flicker for Incandescent Lamps

For sinusoidal supply, 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 per Eq. 1-8.

$$f_M = |f_0 - f_{ih}| \qquad \textbf{Eq. 1-8}$$

Where,

f_0 is fundamental frequency and

f_{ih} is interharmonic frequency

For lower frequency interharmonics(f_{ih} •$2f_0$) and low modulation frequency(f_M • 15 Hz), there in enough RMS voltage fluctuations to cause flicker which IEC flickermeter is capable of detecting. Higher frequency interharmonics ($f_{ih} > 2f_0$) do not cause enough RMS variation to result in any flicker.

Impact of Interharmonics on Flicker for CFLs and LED Lamps

Flicker performance of CFLs and LED lamps has been compared with those of incandescent lamps in the presence of interharmonics [11]. Experimental results (see sensitivity curves in **Error! Reference source not found.**) indicate that their flicker performance is similar to that of incandescents for interharmonics below 2nd harmonic. These lamps continue to be sensitive to interharmonics around higher order harmonics (e.g. 3rd and 5th) where flicker is not an issue for incandescents. This may be attributed to the use of diode bridge rectifier in LED lamps and CFLs.

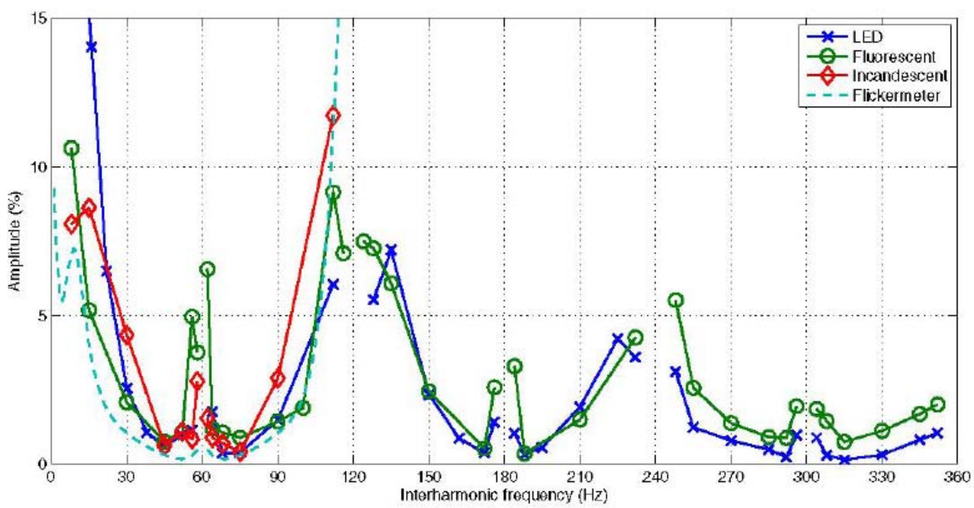


Figure 1-9.
Minimum Interharmonic Amplitude Generating Perceptible Flicker over a Frequency Range [11]

Impact of Interharmonics on IEC Flickermeter Response

As mentioned before, computations in IEC compliant flickermeters are based on the measurement of fluctuations in RMS supply voltage. It means that these meters are capable of detecting flicker only due to low-frequency interharmonics (below 2 f_0) as higher order interharmonics do not cause much RMS variation. As a result, the existing version of flickermeters are suitable only for incandescent lamps. In addition, these meters have been found to be unable to detect flicker for interharmonics above 102 Hz. This may be attributed to cut-off frequency of 42 Hz for the bandpass filter in Block 3 of the flickermeter[11]. Based on these observations, it can be concluded that IEC flickermeters in their existing form are not capable of accurately detecting flicker due to interharmonics. The recommended solution to the problem lies in using amplitude-only interharmonic limits that are recommended to be incorporated in the latest revision to IEEE Std 519 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”(See Figure 1-10).

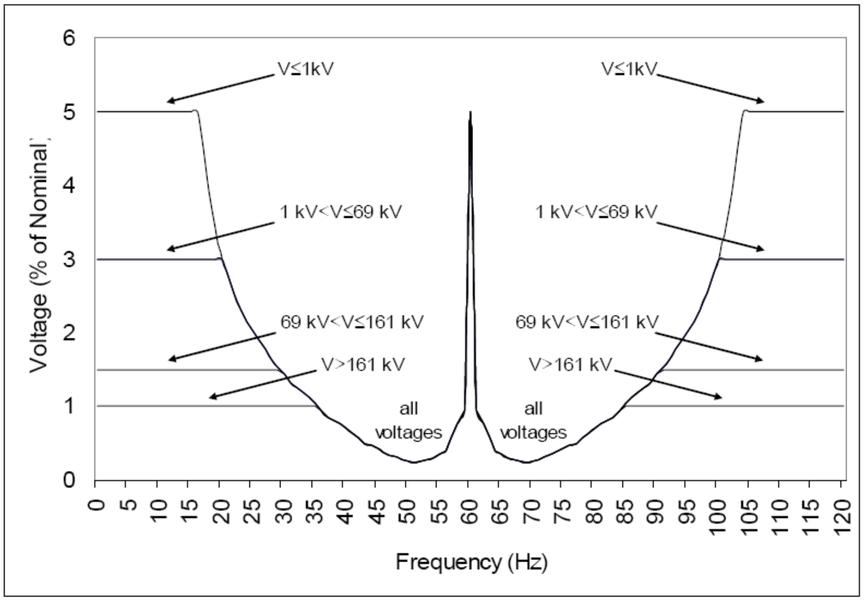


Figure 1-10.
Voltage-only Interharmonic Limits Based on Flicker in Revised IEEE Std 519

2
RECOMMENDATIONS FOR FLICKER LIMITS AND EVALUATION PROCEDURE

This chapter summarizes recommended planning levels and 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 the international standards (IEC Standard 61000-3-7) and referenced in the IEEE Standard (IEEE Standard 1453).

Three different voltage levels are defined in Table 2-1. The flicker planning levels are developed as a function of these voltage categories. 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 point of common coupling with customers that may have fluctuating loads. These planning levels are designed to make sure that the flicker levels at LV (low voltage) connection points does not actually exceed the “compatibility level” that is defined to help assure proper operation of customer equipment.

Table 2-1.
System Voltage Levels

System	System Voltage (U_N)
LV	U_N • 1 kV
MV	1 kV <U_N • 35 kV
HV	35 kV <U_N • 230 kV
EHV	U_N > 230 kV

Planning Levels

Indicative Values

The planning levels (denoted as L_{Pst} and L_{Plt}) recommended for MV, HV and EHV points of common coupling are shown in Table 2-2. The planning levels are developed to be the basis for applying emission limits for individual customers with points of common coupling at these different voltages. The individual customer emission limits are developed using a procedure that allots each customer some portion of these total planning levels. Emission limits for individual loads (denoted as E_{Pst} and E_{Plt}) are set so that the aggregate effects do not exceed these planning levels.

Table 2-2.
Planning Levels for P_{st} and P_{lt} in MV, HV, and EHV Power Systems

	Flicker Planning Levels	
	MV	**HV-EHV**
P_{st}	0.9	0.8
P_{lt}	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 Pst values measured at the same time in two locations:

$$T_{PstAB} = \frac{P_{st}(B)}{P_{st}(A)} \qquad \textbf{Eq. 2-1}$$

The methods to compute transfer coefficient in absence of any measurements are detailed in Appendix A. An example of the impact of the transfer coefficient between HV and LV having a value of 0.8 is reflected in the revised indicative planning level for HV system as.

$$L_{PstHV} = \frac{0.8}{T_{PstHL}} = \frac{0.8}{0.8} = 1.0 \qquad \textbf{Eq. 2-2}$$

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

Evaluation – Assessment Procedure

The following evaluation procedure is recommended for ongoing evaluation against the determined planning levels. The procedure is based on continuous monitoring with a flickermeter that is compliant with IEEE Standard 1453. 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 the previous

chapter. 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) 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) 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.

   i. 95% probability value should not exceed the planning level

   ii. 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.

Evaluating Acceptance of Fluctuating Loads – Determining Individual Customer Emission Limits

IEC Standard 61000-3-7 recommends a three-step procedure for evaluating acceptance of fluctuating loads.

Stage 1 – Automatic Acceptance

This procedure permits acceptance of a potential customer without the need of any detailed analysis. This criterion puts limit on the allowable ratio of load power variation (S) to the System Short Circuit capacity (S_{SC}) at PCC (See

Table 2-3, **Error! Reference source not found.**).

Table 2-3.
Allowable Load Fluctuations for Automatic Acceptance of Fluctuating Loads

Number of variations per minute(r)	ΔS/ SSC (%)
r > 200	0.1
10 ≤r≤ 200	0.2
r < 10	0.4

Stage 2 – Allocating Emission Limits based on Load Power

Flicker limits are established for each individual customer. However, the overall flicker level being experienced at any point on the power system is the combined effect of all the fluctuating loads being supplied by the system. This needs to be taken into account while developing limits for individual customers.

For fluctuating loads in MV systems that do not meet the criteria in Stage 1, emission limits (E_{Psti}, E_{Plti}) are allocated for individual load (S_i) based on its share of the total load (S_{MV}) connected to a common supply system. The expression for computing E_{Psti} is given below. Similar expression can be used for computing E_{Plti}.

$$E_{Psti} = G_{PstMV} * \sqrt[3]{\frac{S_i}{S_{MV} * F_{MV}}}$$

$$G_{PstMV} = \sqrt[3]{L_{PstMV}^3 - T_{PstHM}^3 * L_{PstHV}^3}$$

Where,

G_{PstMV} – Maximum global contribution of local loads to the flicker level in the MV system

L_{PstMV} – Planning level of the flicker level in the MV system

T_{PstHM} – Flicker transfer coefficient from the upstream HV system to the MV system (typical value is 0.8)

L_{PstHV} – Planning level of the flicker level in the upstream HV system

F_{MV} – Coincidence factor (typically 0.2 to 0.3 to represent the non-simultaneous variations)

Basic levels for emission limits (E_{Psti} = 0.35, E_{Plti} = 0.25) may be allowed for all the loads in order to prevent excessive restrictions on smaller loads.

The similar approach can be used for HV and EHV systems. However, the emission limits (E_{Psti}, E_{Plti}) are based on the total power available to the HV (EHV) users instead of the total supply capacity of the system. The expression for computing E_{Psti} for HV system is given below. Similar expression can be used for computing E_{Plti}.

$$E_{Psti} = G_{PstHV} * \sqrt[3]{\frac{S_i}{S_{tHV}}}$$

Where,

G_{PstHV} – Maximum global contribution to the flicker level of all fluctuating installations that can be connected to the considered HV system

S_i - Agreed Power of user *i*

S_{tHV} - Part of the total supply capacity of the HV considered system that is devoted to the HV users

Like in MV systems, basic levels for emission limits (E_{Psti} = 0.35, E_{Plti} = 0.25) may be allowed for all the loads in order to prevent excessive restrictions on smaller loads.

Stage 3 – Acceptance of Higher Emission Limits in Exceptional Cases

If a load is unable to meet the emission limits as identified in Stage 2 analysis, a more thorough analysis is required. In rare cases, the emission limits may be relaxed to some extent if there are enough margins in the planning levels. A typical scenario is that a portion of the available capacity of network may not be taken up for a long time. Such allowance should consider the existing background levels and it warrants a careful study of the connection. Such a step can allow the postponing of investment in flicker mitigation solutions which may never be required.

Assessment Procedure - Evaluating Compliance with Emission Limits

IEC Standard 61000-3-7 recommends the following *Assessment Procedure:*

Flicker should be measured at the point of common coupling (PCC) between the disturbing load and the flickering lighting load. It is recommended to monitor all the three phases as they may be experiencing different flicker levels. Figure 2-1 illustrates a possible scenario of welders on a radial feeder.

In this case the metering point A is nearest to the point of common coupling 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. The point B may also help to determine if actions like adding reactance or closing in the bus tie to increase short circuit availability will help in mitigating fluctuations.

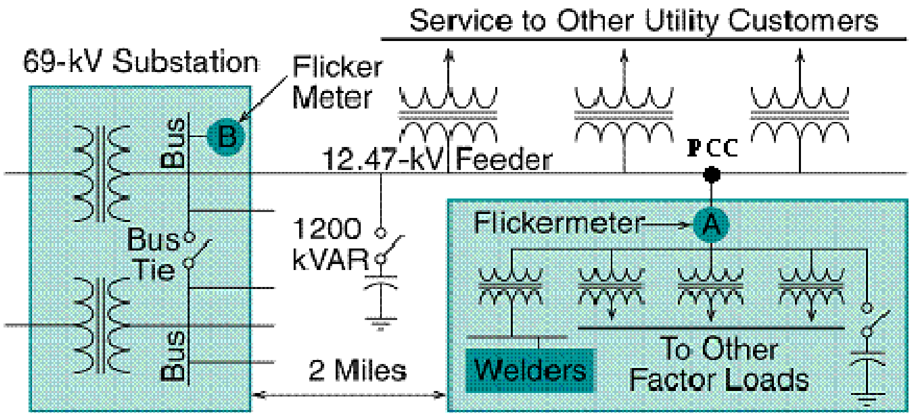


Figure 2-1.
Point of Common Coupling (PCC) between Flicker-Producing Customer and Other Customers in the System

The following evaluation procedure is recommended for ongoing assessment of compliance with the flicker limits at PCC with the supplying power system. The procedure is based on continuous monitoring with a flickermeter that is compliant with IEEE Standard 1453. 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.

1. 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.

$$E_{Pstactual} = E_{Pstnominal} * \frac{S_{scnominal}}{S_{scactual}}$$

2. Obtain an array of P_{st} values for each day resulting in 144 values for each phase.
3. 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 the previous chapter. 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.
4. Combine the P_{st} values for a full week (Sunday midnight to Sunday midnight) and calculate summary statistics for the week.

   $P_{st99\%}$

   $P_{st95\%}$
5. Combine the P_{lt} values for a full week (Sunday midnight to Sunday midnight) and calculate P_{lt} summary statistics for the week.

$P_{lt99\%}$

$P_{lt95\%}$

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

   $P_{stactual}$

7. Calculate the estimated contribution of the customer ($P_{stcustomer}$) to the flicker levels. The procedures for estimating contribution of single customer are presented in the next section.
8. These statistics can be compared with the adjusted customer emission limits.
   i. 95% probability value should not exceed the emission limit
   ii. 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.
9. Plot time trends (See Figure 2-2) and histograms of the flicker data as needed for additional illustration of the flicker variations. These plots can be obtained for individual days or for the entire week.

A sample format of the flicker report that can be automatically generated by PQView at the end of the evaluation period of a week is provided in Appendix B of this report. This report provides information about flicker trends and a summary of flicker indices. An alarm will be issued if the flicker levels were to exceed the specified limits.

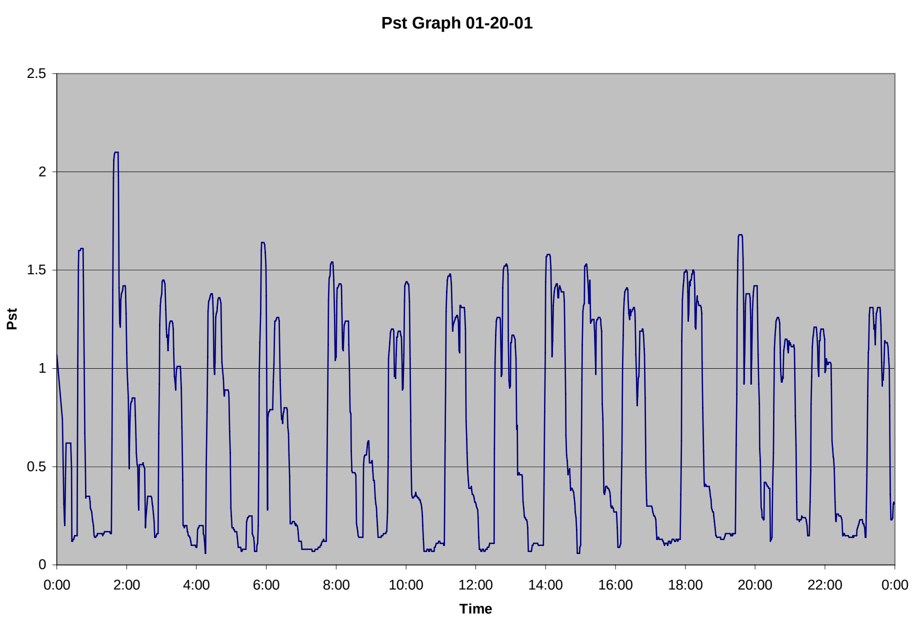


Figure 2-2.
Example time trend of P_{st} at an arc furnace PCC

Estimating Flicker Contribution of Single Customer

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

Low Background Flicker Levels

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

Let's assume that the limit for the acceptable level of flicker at the PCC for a new customer is set at

$$P_{st99\%} = E_{Pst}$$

Then we measure the background levels of flicker before connecting the customer (this should be done over at least a two week period) and we get

$$P_{st99\%} = P_{stbackground}$$

Finally we measure the actual levels of flicker after connecting the customer and we get

$$P_{st99\%} = P_{stactual}$$

The flicker being caused by the new customer can be estimated by assuming the flicker levels add by a cubic summation. However, this may not be accurate in some cases.

$$P_{stactual} = \sqrt[3]{P_{stcustomer}^{3} + P_{stbackground}^{3}}$$

Then

$$P_{stcustomer} = \sqrt[3]{P_{stactual}^{3} - P_{stbackground}^{3}}$$

This is the estimate for the flicker being caused by the customer at this PCC. This value can be compared with the customer flicker limit:

$$P_{stcustomer} \textit{ should be less than } E_{Pst}$$

The sample calculations for such a scenario are provided in Appendix C. As a practical measure, the background flicker will typically have to be measured before the steel mill or other major industrial facility 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.

High Background Flicker Levels

If the background flicker levels are substantial ($P_{stbackground} > 0.5$), the method in the previous section can result in significant errors. Other methods that are suitable in such conditions are under review by industry groups like IEEE and IEC. One such method that involves correlation between the fluctuating current and the observed voltage fluctuations to determine the emission level of a particular fluctuation load is presented here [3].

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 is also 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. For example, one may need to use this method at primary metering of a facility that is few miles downstream of actual PCC. The procedure for the implementation of this approach is presented here (See Figure 2-3):

1. Measure the voltage waveform ($V_M(t)$) at the point of evaluation (POE) and current waveform ($i_M(t)$) drawn by the flicker source.
2. Use $V_M(t)$ to compute P_{stPOE} using IEC method [2]. This represents the overall flicker levels at the POE.
3. 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.

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

   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 following equation.

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

4. Use $V_E(t)$ to compute $P_{stemission}$ 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.

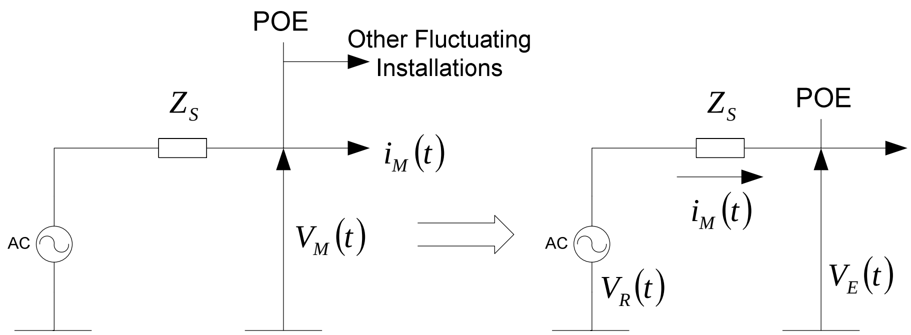


Figure 2-3.
Measurement Based Approach for Estimating Flicker Contribution of Single Customer [3]

Infrequent Events

IEC Standard 61000-3-7 classifies the voltage changes due to motor starting and capacitor switching as rapid voltage changes as the changes are sustained over several cycles (See Figure 2-4). The indicative planning levels in Table 2-1 may be used to determine emission limits for such changes for individual customers based on the number of changes.

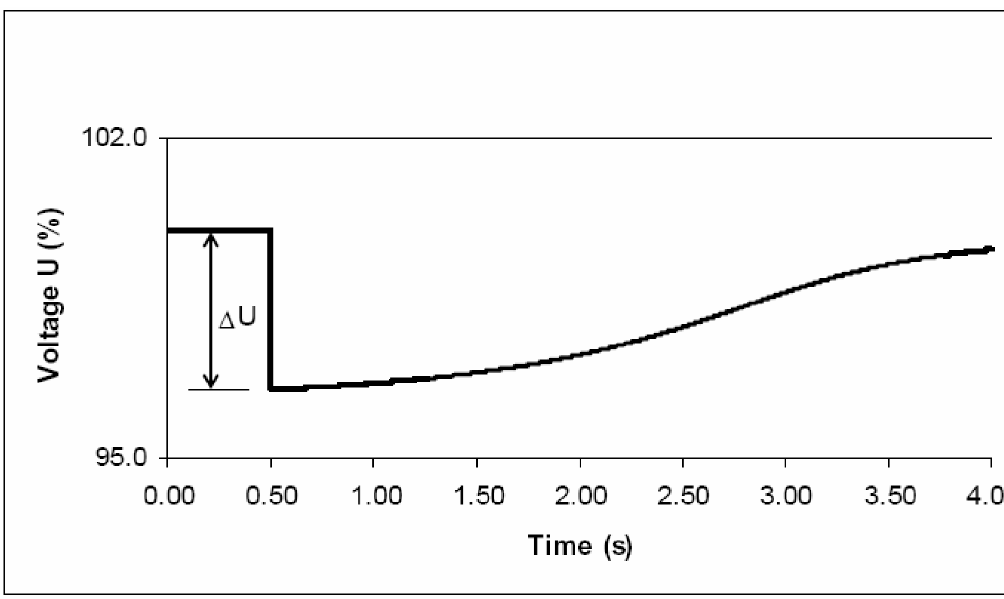


Figure 2-4.
Example Rapid Voltage Change due to Motor Starting

Table 2-4.
Indicative Planning Levels for Rapid Voltage Changes

Number of Changes N	ΔU/Un (%)	
	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

An evaluation tool is presented in the next chapter that may be used to predict the voltage drop at PCC based on the motor and the system characteristics. It can also be used to evaluate the impact of the various mitigation technologies such as the series cap, starting cap, SVC (Static Var Compensator) and reduced voltage starters.

3
ESTIMATING FLICKER LEVELS AT PCC

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 “Pst = 1 curve”(Figure 3-1 and Table 3-1) for estimating flicker levels. This method is only suitable where the load cycle and the resultant voltage profile at PCC are known e.g. motor starting, rolling mill and resistive spot welding.

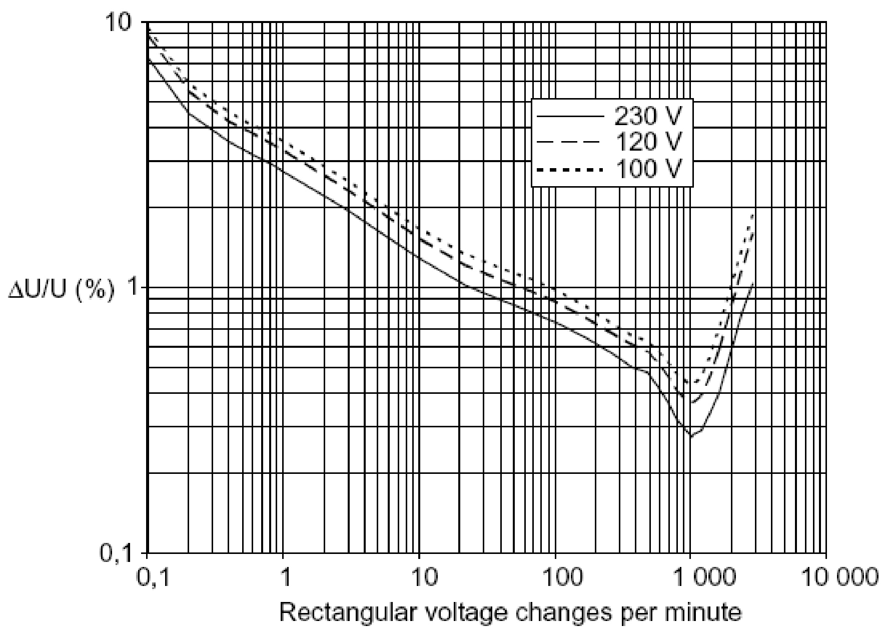


Figure 3-1.
Pst = 1 Curve for Rectangular Voltage Changes [3]

Table 3-1.
Pst = 1 Test Points for Rectangular Voltage Fluctuations

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 $\Delta V/V$ (%)	Col.4 Pst=1 Relative voltage changes for unit flicker severity for 120 V lamps $\Delta V/V$ (%)
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

Use of Shape Factors

The flicker severity can be computed using the following equation:

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

Where,

F is a shape factor (See Figure 3-2, Figure 3-3, and Figure 3-4). For motor-starting without inrush mitigation, a value of 1 may be used for F.

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

$$d = \frac{\Delta U}{U_N} \approx \frac{\Delta S_i}{S_{SC}}$$

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

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

$$d = \frac{\sqrt{3}.\Delta S_i}{S_{SC}}$$

For systems with low X/R (less than 5), use the following equation

$$d = \frac{R_L * \Delta P + X_L * \Delta Q}{U_N^2}$$

$d_{Pst=1}$ is obtained using the plot in Figure 3-1.

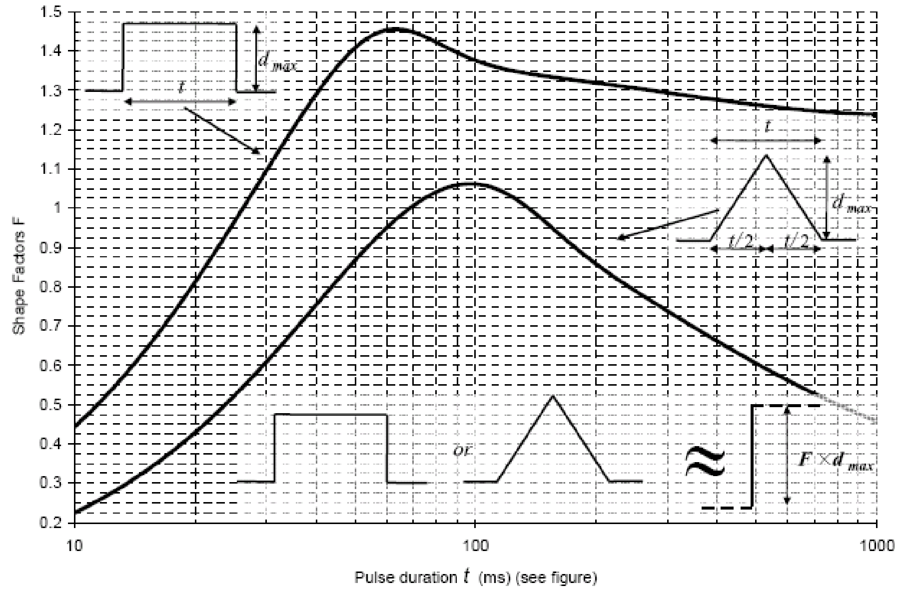


Figure 3-2.
Shape factor for Pulse and Ramp Changes [3]

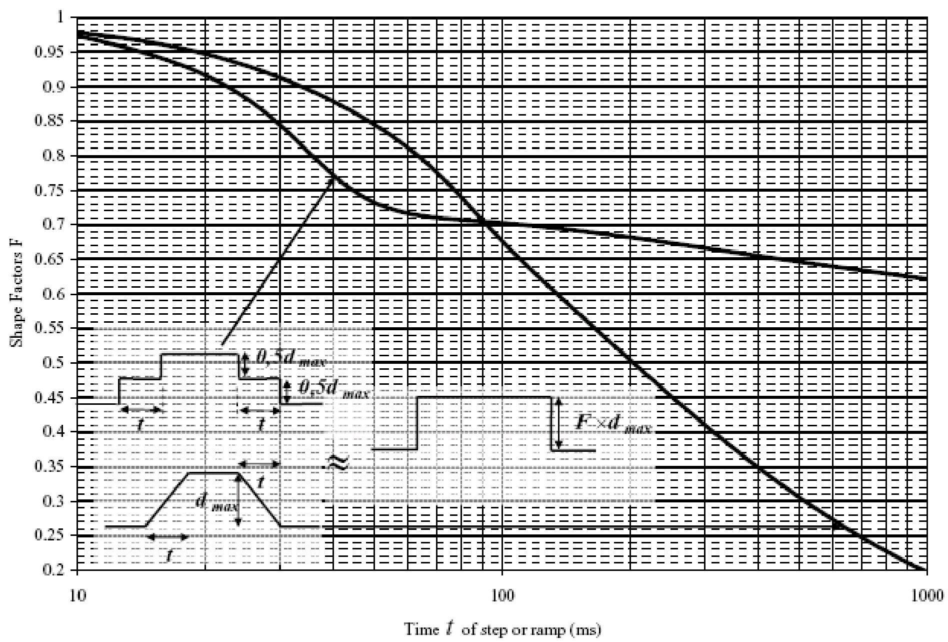


Figure 3-3.
Shape factor for Double Step and Double Ramp Changes [3]

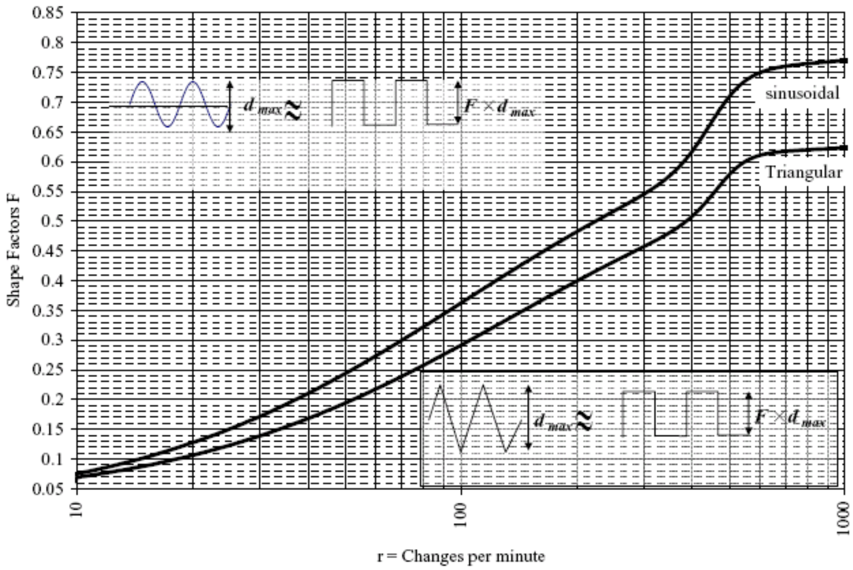


Figure 3-4.
Shape factor for Sinusoidal and Triangular Pulses [3]

Rolling Mill

A rolling mill example is presented here from IEC Standard 61000-3-7. The expected voltage profile at PCC due to the operation of the mill is shown in Figure 3-5.

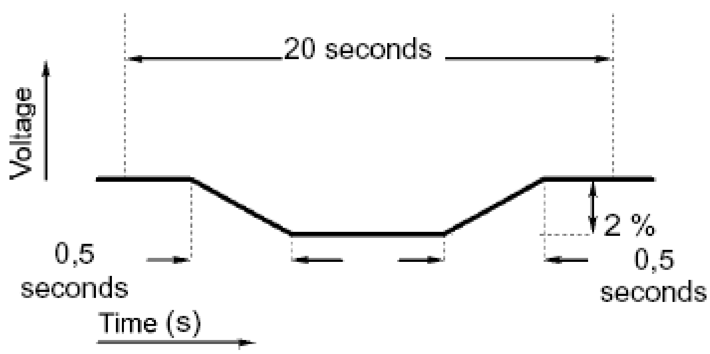


Figure 3-5.
Expected Voltage Profile at PCC due to Rolling Mill

Relative voltage change (d) = 2 %

Shape Factor (F) = 0.31 (From Figure 3-3)

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

$d_{Pst=1}$=1.9 (From Figure 3-1 for 120 V system)

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

Resistive Spot Welding

Resistive spot welders are also a source of voltage fluctuations which can cause flicker if the fluctuations are severe enough. Typical cycle involves electrodes moving to a weld position, electrodes squeezing the welding material, making the weld, holding the material, release and then move to the next welding position. The welding itself requires 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 which 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 PCC due to a spot welder operation is shown in Figure 3-6 [3]. 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 3-2)

Number of voltage changes in one minute = 600

$d_{Pst=1}$=0.5 (From Figure 3-1 for 120 V system)

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

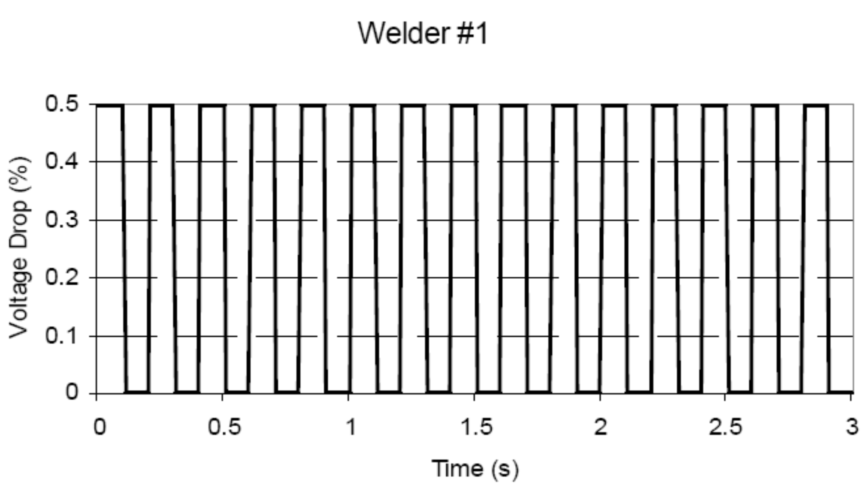


Figure 3-6.
Voltage Drop at PCC due to Welder Operation

A simulation based approach should be used for an accurate assessment especially if multiple 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 he uses a single-phase welder, use the phase(s) which 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 [12]
- 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 like arc furnaces where the wave shape is random and irregular. For such loads, the method based on the actual measurements is presented in the next section.

Estimating Flicker Levels for Arc Furnaces

The 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 is melted from the heat created by the arc. Arc furnaces have melting cycles that last on the order of 30 minutes to two hours; creating randomly shaped impressions on 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 by arc furnaces is unusual in that it contains components from zero (DC) to several hundred Hertz. The unstable nature of an arc is partly the reason for the randomness.

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 (See Chapter 2), different weighting factors are used for the different voltage levels (e.g. 230V in Europe) around the world.

Short Circuit Voltage Depression (SCVD)

Standardizing the method of characterizing flicker (using P_{st}) provides the opportunity to characterize the performance of flicker producing loads and compare the performance from one facility to another.

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 point of common coupling. A method of characterizing this short circuit capacity in terms of the size of the furnace is the SCVD (Short Circuit Voltage Depression):

$$SCVD = \frac{\nabla U}{U}(\%) = \frac{Scc_f}{Scc_n}$$

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 for 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 assuming 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 arc furnace facilities. Figure 3-7 illustrates some of these results as a function of the short circuit voltage depression level (without compensation). It is clear that there is a direct relationship between the flicker severity and the short circuit voltage depression level. Note that these results are for ac arc furnaces and we will use this as the base case for evaluation.

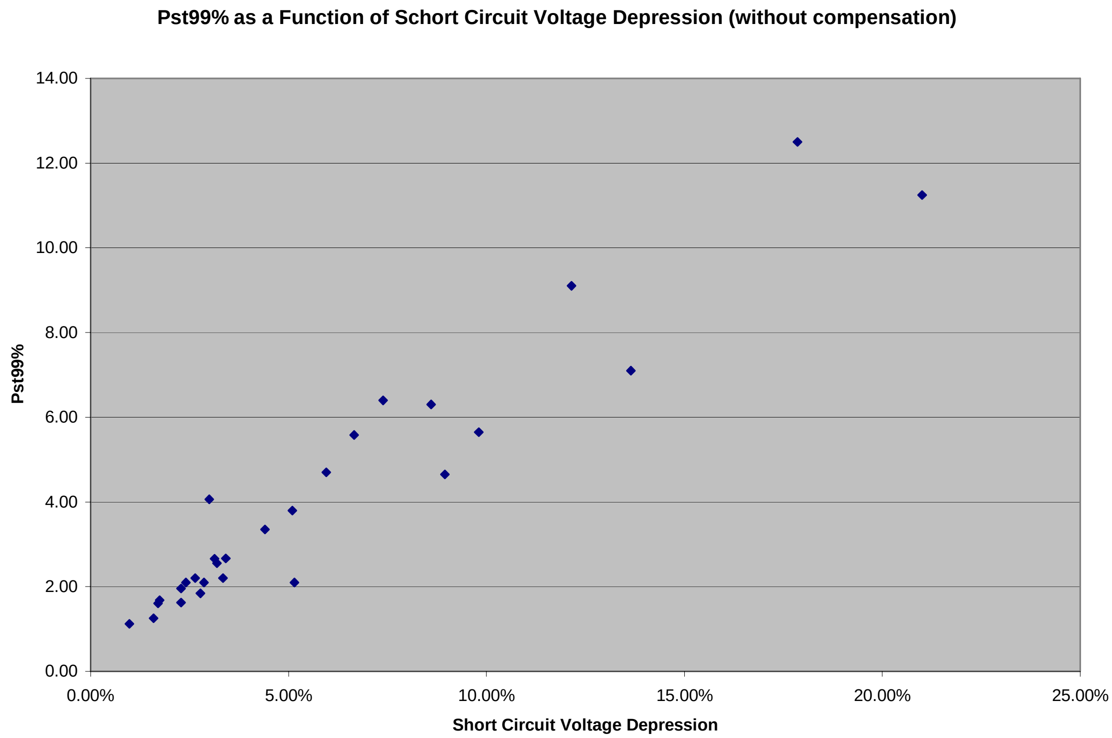


Figure 3-7.
Pst99% Levels as a Function of the Short Circuit Voltage Depression Level for Arc Furnace Facilities

The Arc Furnace Kst

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

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

K_{st} is a measure of the arc furnace flicker causing characteristics independent of the effect of the short circuit strength. Figure 3-8 illustrates K_{st} values plotted as a function of the arc furnace size. IEC Std 61000-3-7 [3] recommends using a value ranging between 58 and 70 for estimating purposes. However, a value of 85 is commonly used for high grade steel such as stainless. However, it should be noted that values of over 100 have been shown to exist [13], [14].

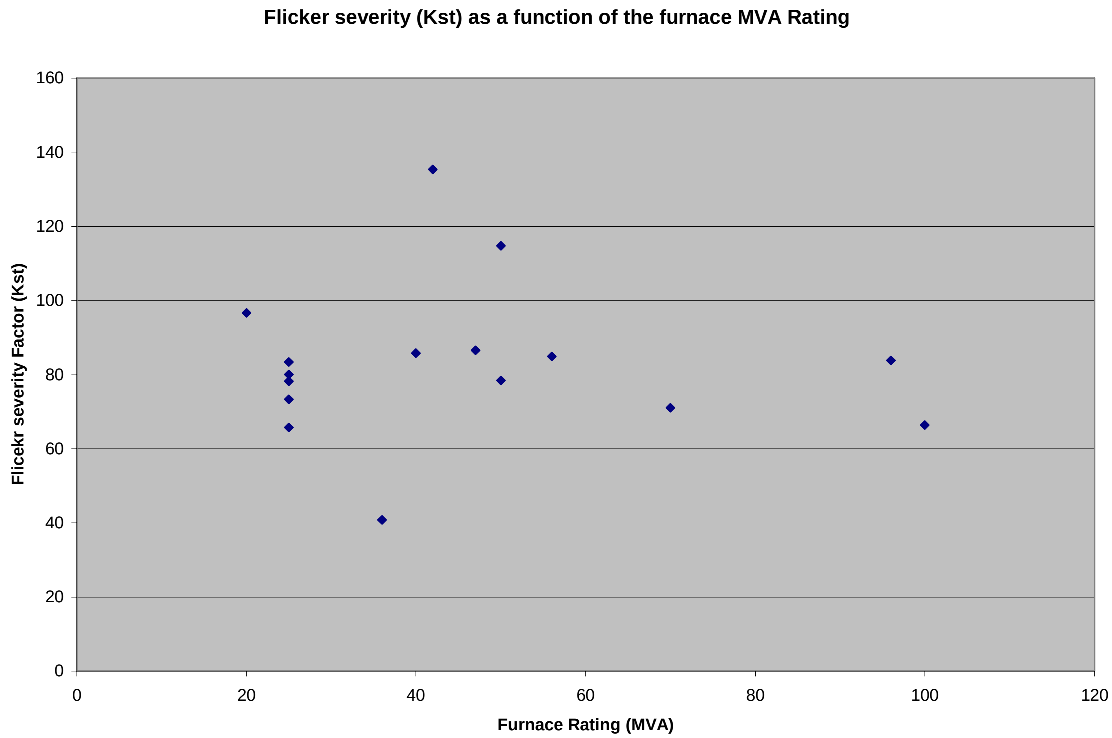


Figure 3-8.
Flicker Severity Factor as a function of the Furnace MVA Rating

It may be possible to obtain estimated *Kst* 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, etc.

Correction for Type of Furnace

If K_{st} estimates are not available from the furnace manufacturer, correction may be applied to the estimate for furnace designs other than typical AC arc furnaces.

For instance, DC arc furnaces will typically have a lower K_{st} value (lower levels of flicker for the same furnace size) and furnaces with high reactance designs may also have lower K_{st} values.

The 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. Therefore, a reasonable assumption for a DC arc furnace K_{st} would be 60*0.75 or 45 (systems with 120 volt lighting).

It is also 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.

Effect of Static Var Compensators

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 about 40% reduction of flicker levels with optimized controls. However, the amount of flicker reduction is very dependent on the SVC size and control characteristics.

Newer compensators known as STATCOM (Static Compensator) can be used for even better reduction of flicker levels. These systems can be designed for very fast control of the voltage fluctuations to achieve just about whatever level of flicker reduction is needed, dependent only on the sizing and controls for the STATCOM. A flicker reduction factor of 3 would be considered typical with a STATCOM.

Summary of Important Factors

Table 3-2 summarizes the important factors for estimating the flicker levels that may be caused by a particular arc furnace facility.

Table 3-2.
Factors affecting the Flicker Levels Resulting from an Arc Furnace Installation

Factor Description	Typical Values
Short circuit capacity at PCC	
Arc furnace short circuit level (electrodes shorted for an ac arc furnace)	2 x furnace MW
Correction for furnace type - high reactance design	0.8-1.0
Correction for furnace type - dc arc furnace	0.5-0.75
Effect of conventional static var system	0.5-0.75
Effect of STATCOM	0.17-0.33

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 kinds of the loads.

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

Where,

m = 4 for arc furnaces run to 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.

Simulation Based Approach

A computer simulation based approach may also be used for evaluating the flicker impacts of fluctuating loads. This approach requires computer modeling of the limited portion of the utility system, customer system including the fluctuating load itself and the flickermeter model that meets the requirements outlined in Chapter 2. Such a model would enable the evaluation of the impact of various system parameters and possible mitigating solutions on the flicker values at points of interest in the system.

EPRI has developed evaluation modules for this purpose by making use of EMTP-RV platform as a part of the program *PS1A - Improving PQ and Reliability with T&D Design, Maintenance, and Planning*. The funders of this project set can download the following modules from EPRI web-site.

Flicker Analysis Module V2.0 Prototype: EPRI, Palo Alto, CA: 2008. 1018362:

Motor Starting Module V2.0 Prototype: EPRI, Palo Alto, CA: 2008. 1018361:

EMTP is a widely used software platform for performing simulation and analysis of transients in power systems. The modules have the capability to evaluate arc furnace, spot welding and induction motor starting operations. The arc furnace model is in the process of being modified using the contribution from Southern Company [14] and will be available for use in the version upgrade that is scheduled for end of 2009.

Arc Furnace Operation

The base circuit that has been developed for the flicker analysis of arc furnace operation is shown in Figure 3-9. The utility system is represented by the short-circuit equivalent at PCC. The models are included for individual components of the customer system including step-down transformers, capacitor banks (tuned/un-tuned), series reactor, furnace transformer secondary impedance (includes delta, cables, mast arms and electrodes), and arc itself. The flicker at the desired nodes in the circuit can be monitored using the flickermeter models. The system parameters for the base circuit are shown in Appendix D.

The arc furnace model that has been used simulates the initial bore-in period of the melt cycle that can be associated with *Pst99%* value. It achieves this by modeling the random variations in arc length using uniform distribution.

The module allows the user to plot instantaneous flicker values (P_{inst}) as well as compute P_{st} due to arc furnace operation. Average P_{st} output of 3.87 at PCC (See Table 3-3) obtained from simulation falls within the range that is obtained for $P_{st99\%}$ using the hand calculation approach (See next sub-section) that takes into account furnace rating and system short circuit capacity.

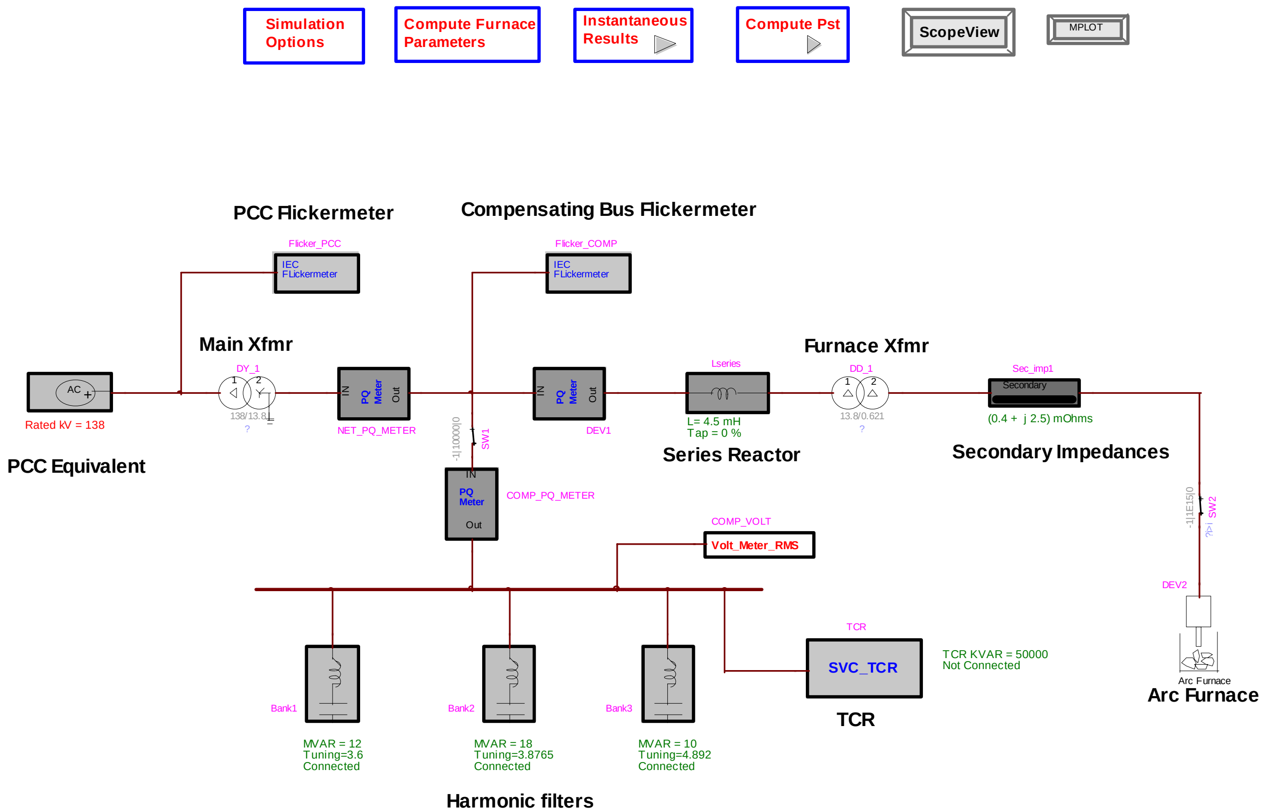


Figure 3-9.
Base Circuit for Arc Furnace Evaluation

Table 3-3.
Base Case Results

	Flicker (Pst)	
	PCC	**Compensating Bus**
Phase A	3.78	18.18
Phase B	3.78	16.66
Phase C	4.06	17.94
Average	3.87	17.59

Hand Calculation Approach

Impedance Computations (p.u. on 100 MVA Base)

Source impedance:

$Z_{sys} = 0.0098 + j0.044$

Substation transformer (45 MVA) impedance:

$Z_{st} = (0.007 + j0.0739) * 100/45 = 0.0156 + j0.1642$

Series Reactor impedance at 0% Tap

$Z_{sr} = 0$

Furnace transformer (35 MVA) impedance:

$Z_{ft} = (0.002 + j0.02) * 100/35 = 0.0057 + j0.057$

Furnace transformer secondary impedance (delta, cable, electrodes etc.)

$Z_{\sec} = 0.1037 + j0.9136$

Total impedance

$Z_{total} = Z_{sys} + Z_{st} + Z_{sr} + Z_{ft} + Z_{\sec} = 0.1348 + 0.9136$

Short Circuit Voltage Depression calculation

$$Scc_f(MVA) = \frac{100}{|Z_{total}|} = 108$$

$$Scc_n(MVA) = 2218$$

$$SCVD = \frac{Scc_f}{Scc_n} = 0.0488$$

Flicker Estimation

$P_{st95\%} = K_{st} * SCVD$

$P_{st99\%} = 1.3 * P_{st95\%}$ [3]

Assuming *Kst* range of 58 and 70, $P_{st99\%}$ is expected to fall between a value of 3.68 and 4.44.

Impact of Source Strength

Flicker at PCC is directly proportional to the ratio of the short circuit strength of the furnace at PCC to the fault level of the system at PCC. Stronger source (higher fault levels) means that the flicker at PCC is likely to be lower. The impact of the source strength on flicker values is studied by varying the source impedance and the corresponding results are shown in Table 3-2. It can be seen that *Pst* values are directly proportional to the source impedance.

Table 3-4.
Impact of Source Strength

PCC Equivalent Parameters	Normal Strength	10 % Stronger	10% Weaker
R0 (%)	1.55	1.395	1.705
X0 (%)	7.05	6.345	7.755
R1 (%)	0.98	0.882	1.078
X1 (%)	4.4	3.96	4.84
Pst Results			
PCC- Phase A	3.78	3.49	4.35
PCC- Phase B	3.78	3.38	4.07
PCC- Phase C	4.06	3.53	4.29
PCC- Average	3.87	3.47	4.24
Compensating Bus - Phase A	18.18	17.6	18.45
Compensating Bus - Phase B	16.66	16.85	17.45
Compensating Bus - Phase C	17.94	16.71	17.2
Compensating Bus - Average	17.59	17.05	17.70

Impact of Series Reactor

Use of series reactor is beneficial in reducing flicker as it helps to stabilize the arc and also serves to reduce the short circuit capacity of the furnace at PCC. The impact of the series reactor on the flicker values is studied by varying the tap position on the reactor and recording the resultant *Pst* values. It is found that Pst values are progressively mitigated with increase in tap position (See Table 3-5). Also, the reduction is proportional for the two meters as both of these measurement locations are behind the series reactor.

Table 3-5.
Impact of Series Reactor

Pst Results	Tap Position (%)		
	0	50	100
PCC- Phase A	3.78	2.67	2.17
PCC- Phase B	3.78	2.55	2.12
PCC- Phase C	4.06	2.48	2.01
PCC- Average	3.87	2.57	2.10
Compensating Bus - Phase A	18.18	11.32	9.17
Compensating Bus - Phase B	16.66	11.77	9.71
Compensating Bus - Phase C	17.94	11.62	9.49
Compensating Bus - Average	17.59	11.57	9.46

Impact of SVC

For this option, it is suggested to adjust the main time step in “Simulation Options” to a value of 50 us. The value may be reverted to 400us after this simulation is over. The connected field of the TCR block is checked for this simulation. The parameters of all the other components remain the same. The resultant values are shown in

Table 3-6.

Table 3-6.
Impact of SVC

Pst Results	TCR Status	
	Disconnected	Connected
PCC- Phase A	3.78	2.26
PCC- Phase B	3.78	2.32
PCC- Phase C	4.06	2.34
PCC- Average	3.87	2.31
Compensating Bus - Phase A	18.18	10.67
Compensating Bus - Phase B	16.66	10.27
Compensating Bus - Phase C	17.94	10.68
Compensating Bus - Average	17.59	10.54

Motor Starting Operation

Motors cause flicker either by their large starting currents or when their mechanical load is pulsating. The typical starting current of 4-10 times normal running current causes a voltage drop of 5-20% on the circuit serving the motor. Energy efficient motors may have higher starting current requirements than the motors that they replace. Random starting of multiple large motors within a facility that are operating asynchronously will create disturbances more frequently. For constantly pulsating mechanical loads such as a shaker, rock crusher, mine drill, etc. voltage drops are likely to be less than starting however they occur more often.

The base circuit for evaluating induction motor starting operation is shown in Figure 3-10. It includes the model of an induction motor including three options for starting namely:

- Direct-on-line starting
- Reduced voltage (Auto-transformer) starting
- Soft starting.

The circuit includes model of the nearby system including incoming utility feeder, step-down transformer, customer feeder, nearby loads and cap banks. It also includes the options of mitigating voltage drops by making use of starting capacitor, series capacitor and SVC. The rest of the utility system is represented by a source equivalent. The flickermeter models are placed at customer bus and the source bus. The circuit represents a typical configuration but can be modified easily to meet the study requirements. The system parameters for the base circuit are shown in Appendix E.

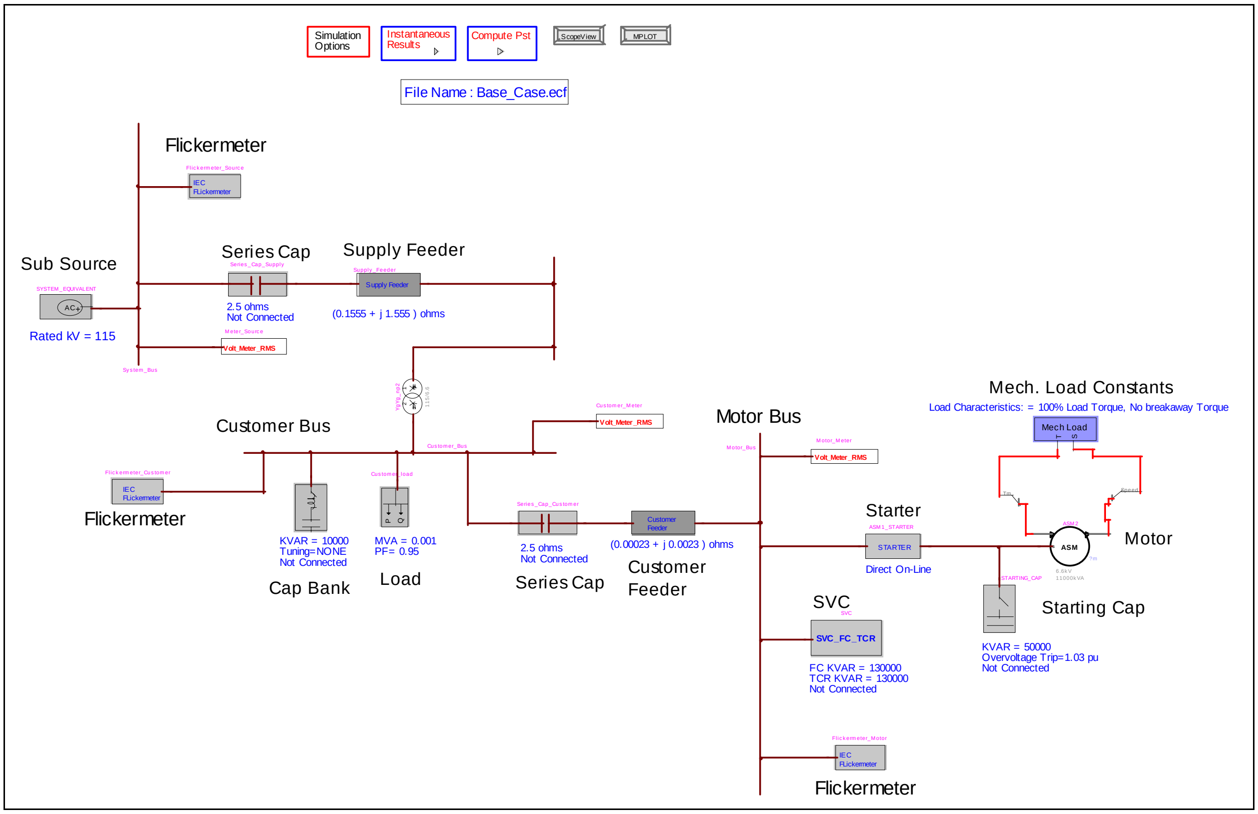


Figure 3-10.
Base Circuit for Motor Starting Evaluation

For Direct-on-line starting, the full voltage appears directly on the motor terminal and the resultant voltage profile at customer and source bus is shown in Figure 3-11. A significant voltage drop can be seen in the nearby system during such an operation. The resultant instantaneous flicker plots at the two locations are shown in Figure 3-12 and the results are tabulated in Table 3-7.

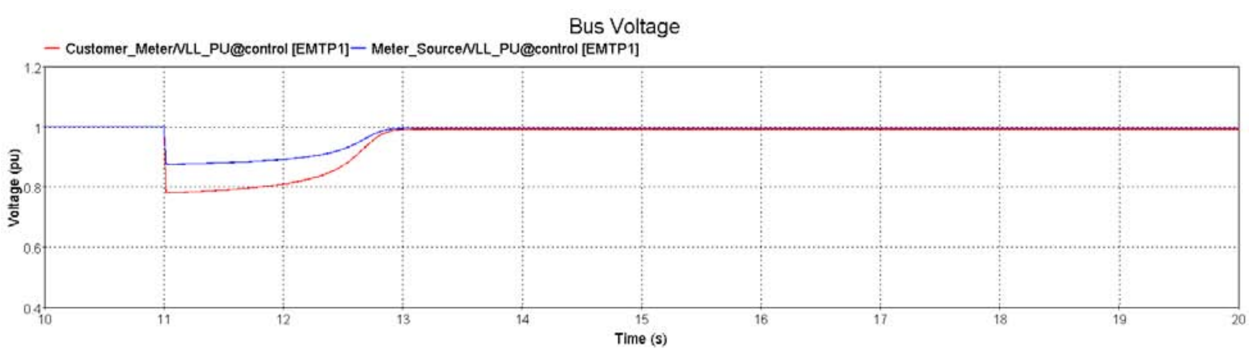


Figure 3-11.
Voltage Profile at Customer and Source Bus for Direct-On-Line Starting

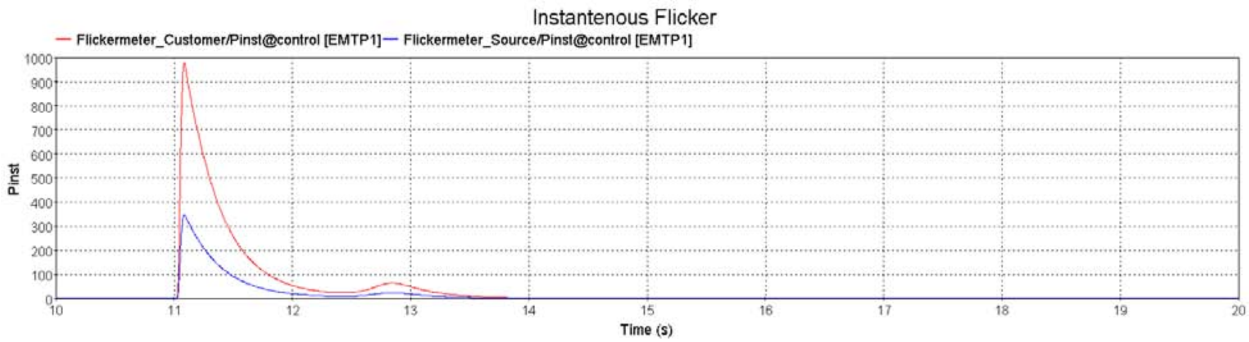


Figure 3-12.
Instantaneous Flicker at Customer and Source Bus for Direct-On-Line Starting

Table 3-7.
Motor Starting Base Case Results

Initial Voltage Drop Level (pu)	
Motor Bus	0.771
Customer Bus	0.778
Source Bus	0.874
Pst	
Motor Bus Phase A	2.32
Customer Bus Phase A	2.27
Source Bus Phase A	1.35

Impact of Motor Size

Base case is the starting point. Rated power of the motor under Main Data tab is adjusted to 5000 kVA. The parameters of all the other components remain the same. The resultant values are shown in

Table 3-8. It can be seen that there is a reduction in voltage drop and flicker values due to reduced motor size.

Table 3-8.
Results for Impact of Motor Size

Initial Voltage Drop Level (pu)	
Motor Bus	0.885
Customer Bus	0.886
Source Bus	0.937
Pst	
Motor Bus Phase A	1.26
Customer Bus Phase A	1.23
Source Bus Phase A	0.71

Impact of Source Strength

Base case is the starting point. The parameters for the source equivalent are adjusted to the following values. The parameters of all the other components remain the same. The resultant values are shown in Table 3-9. It can be seen that there is a reduction in voltage drop and flicker values due to strengthening of the source.

- Source Equivalent
  - Rated Voltage (rms): 115 kV (phase-phase)
  - Actual Voltage (rms): 115 kV (phase-phase)
  - Positive Sequence Resistance: 0.25 % @ 100 MVA
  - Positive Sequence Reactance: 5% @ 100 MVA (60 Hz)

Table 3-9.
Results for Impact of Source Strength

Initial Voltage Drop Level (pu)	
Motor Bus	0.825
Customer Bus	0.832
Source Bus	0.934
Pst	
Motor Bus Phase A	1.84
Customer Bus Phase A	1.77
Source Bus Phase A	0.74

Impact of Reduced Voltage Starter

Customer load and Bank parameters are reverted to the base case values. The parameters for the Starter are adjusted to the following values. The parameters of all the other components remain the same. The resultant values are shown in Table 3-10. It can be seen that there is a reduction in voltage drop and resultant flicker values.

- Starter
  - Option: Reduced Voltage Magnitude Starter
  - Closing Instant: 11 seconds
  - Reduced Voltage Magnitude: 0.5 pu
  - Reduced Voltage Duration: 2 second

Table 3-10.
Results for Impact of Reduced Voltage Starter

Initial Voltage Drop Level (pu)	
Motor Bus	0.932
Customer Bus	0.934
Source Bus	0.963
Pst	
Motor Bus Phase A	1.68
Customer Bus Phase A	1.63
Source Bus Phase A	0.96

Impact of Soft Starter

The parameters for the Starter are adjusted to the following values. The parameters of all the other components remain the same. The resultant values are shown in

Table 3-11. It can be seen that there is even more reduction in voltage drop and resultant flicker values.

- Starter
    - Option: Soft Starter
    - Closing Instant: 11 seconds
    - Ramp duration: 9 seconds
    - Starting firing angle delay: 90 deg

Table 3-11.
Results for Impact of Soft Starter

Initial Voltage Drop Level (pu)	
Motor Bus	0.908
Customer Bus	0.839
Source Bus	0.833
Pst	
Motor Bus Phase A	0.83
Customer Bus Phase A	0.81
Source Bus Phase A	0.5

Impact of Starting Bank

The parameters for the Starting Bank are adjusted to the following values. The parameters of all the other components remain the same. The resultant values are shown in Table 3-12.

- Starting Bank
  - Bank rating: 50000 kVAR
  - Rated voltage: 6.6 kV (phase-to-phase)
  - Overvoltage Setting: 1.03 pu
  - Connected: Checked

Table 3-12.
Results for Impact of Starting Bank

Initial Voltage Drop Level (pu)	
Motor Bus	0.829
Customer Bus	0.833
Source Bus	0.901
Pst	
Motor Bus Phase A	2.08
Customer Bus Phase A	2.02
Source Bus Phase A	1.14

Impact of SVC

The parameters for the SVC are adjusted to the following values. The parameters of all the other components remain the same. The resultant values are shown in Table 3-13.

- SVC
    - Bus voltage: 6.6 kV (phase-to-phase)
    - Fixed Cap Rating: 130000 KVAR
    - TCR Rating: 130000 KVAR
    - Kp: 15
    - Ki: 2600
    - Droop: 0.03 pu
    - Connected: Checked

Table 3-13.
Results for Impact of SVC

Initial Voltage Drop Level (pu)	
Motor Bus	0.893
Customer Bus	0.894
Source Bus	0.929
Pst	
Motor Bus Phase A	0.88
Customer Bus Phase A	0.86
Source Bus Phase A	0.56

4
BASIS FOR CUSTOMER AGREEMENTS

In this chapter a draft template for customer agreements is provided that can be the basis for defining relative responsibilities and assessment methods for customer installations that may cause flicker problems.

Flicker Requirements

Limits

Flicker will be assessed at the Point of Common Coupling (PCC) using an instrument in compliance with IEEE Standard 1453. 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 me met for compliance:

I. 95% probability value should not exceed the emission limit

II. 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.

Prior to Startup

If background flicker levels are a possible concern, background levels (Pstbackground) 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 (Pst and Plt) 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 (Smax)

- Load power variation (S)
- Number of variations per minute (r)
- Alternatively, the *Kst* value for loads like arc furnaces should be provided

This information in conjunction with the system short circuit capacity and system voltage level may be used to evaluate if the fluctuating load meets the automatic acceptance criteria (See Chapter 2).

In the case of an electric arc furnace facility, the following information may be requested to estimate the expected flicker levels using the methodology in Chapter 3.

- Furnace Type – DC/AC
- High reactance design
- Furnace MW
- Furnace Kst
- Mitigating technology planned– SVC/STATCOM

Compliance on an Ongoing Basis- After start-up

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 a flicker monitor that is compliant with IEEE Standard 1453. 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.

1. Obtain an array of *Pst* values for each day resulting in 144 values for each phase.
2. Calculate an array of *Plt* values for each day. Each *Plt* value is calculated from twelve *Pst* values spaced 10 minutes apart using a cubic relationship as described in the previous chapter. It is recommended that sliding window approach be used in which the oldest *Pst* measurement is replaced by the newest *Pst* value at each 10 minute interval resulting in 144 *Plt* 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 *Pst* values for a full week (Sunday midnight to Sunday midnight) and calculate summary statistics for the week.

   Pst99%

   Pst95%
4. Combine the Plt values for a full week (Sunday midnight to Sunday midnight) and calculate Plt summary statistics for the week.

$Plt99\%$

$Plt95\%$

5. The statistical values calculated represent the actual flicker levels. These can be compared with the system flicker compatibility levels. We will refer to these values obtained from the direct measurements as Pstactual (general term for each Pst index, same terminology can be applied to the Plt indices).

$$P_{stactual}$$

6. Calculate the estimated contribution of the customer (Pstcustomer) to the flicker levels. The procedures for estimating the contribution of a single customer are presented in Chapter 2.
7. These statistics can be compared with the specified customer emission limits. Note that the specified customer limits should be adjusted 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 can be performed as follows.

$$E_{Pstactual} = E_{Pstnominal} * \frac{S_{scnominal}}{S_{scactual}}$$

5
GLOSSARY

Compatibility Level:

The specified disturbance level used as a reference level in a specified environment for coordination in the setting of emission and immunity limits. This is normally taken as the level of Pst or Plt above which customer complaints are likely to occur. These levels are not used for assessing individual load compliance.

Extra High Voltage (EHV):

Voltage levels that are greater than 230 kV.

Flicker

Sudden fluctuations in system voltage, which could result in observable changes in the output of lamps.

High Voltage (HV):

Voltage levels that are greater than 35 kV, but less than or equal to 230 kV.

Interharmonics

The non-integer multiple of the fundamental frequency.

Low Voltage (LV):

Voltage levels that are less than or equal to1 kV.

Medium Voltage (MV):

Voltage levels that are greater than1 kV, but less than or equal to 35 kV.

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 large loads and installations, in order to coordinate those limits with all the limits adopted for equipment intended to be connected to the power supply system. In planning studies, this is the level of Pst or Plt used to assess the impact of adding fluctuating loads to the electric power system.

Point of Common Coupling (PCC)

The point on the MV, HV, or EHV bus on the electric power system electrically closest to a particular fluctuating load, at which point other loads are or could be connected.

6
REFERENCES

1. IEEE Standard 1453-2004, “IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems”
2. IEC Standard 61000-4-15, “Flickermeter - Functional and Design Specifications”
3. IEC Standard 61000-3-7-2008, “Assessment of Emission Limits for Fluctuating Loads in MV and HV Power Systems,” 2008.
4. ANSI C84.1-1995, “Electrical Power Systems and Equipment - Voltage Ratings (60 Hz)
5. Halpin, S. Mark et al, “Voltage and Lamp Flicker Issues: Should the IEEE Adopt the IEC Approach.” IEEE Transactions on Power Delivery, Vol. 18, No. 3, July 2003.
6. PQTN Brief No. 24, “Perception Thresholds of Flicker in Modern Lighting,” published by EPRI in 2007.
7. PQTN Brief No. 36, “Lamp Flicker Predicted by Gain-Factor Measurements,” published by EPRI in 2007.
8. PQTN Brief No. 37, “Lamp Flicker in Compact Fluorescent Lamps and four-foot Fluorescent Lighting,” published by EPRI in 2007.
9. R. Cai, J.F.G. Cobben, J.M.A. Myrzik and W.L. King, 2006,”Proposal for improving UIE/IEC Flickermeter,” Proceedings 3rd IEEE Young Researchers Symposium in Electrical Power Engineering
10. Koster, M. De, Jaeger, E, De, and Vancoem, W., “Light flicker caused by Interharmonics,” Laborelec draft paper
11. Kim, T., Rylander, M., Powers, E.J., Grady, W. M.,and Arapostathis, A., “LED Lamp Flicker Caused by Interharmonics,” IEEE International Instrumentation and Measurement Technology Conference, 2008
12. PQTN Case Study No. 1, “Light Flicker Caused by Resistive Spot Welder,” published by EPRI Power Electronics Applications Center, May 1997
13. A. Robert, M. Couvreur, “Arc Furnace Flicker Assessment and Prediction,” Electricity Distribution, 1993, CIRED, 12th International Conference, 17-21 May 1993, Vol. 2.
14. R. Horton, T. Haskew, R. Burch, “A Time Domain AC Electric Arc Furnace Model for Flicker Planning Studies,” IEEE Transactions on Power Delivery, Vol. 24, Issue 2, 2009.
15. H. Renner, M. Sakulin, “Flicker Propagation in Meshed High Voltage Networks,” in Proc. 9th Int. Conf. Harmonics and Power Quality, Vol. 3, Oct. 2000.

16. Horton, R., Haskew T., "Determination of Flicker Transfer Coefficients Near Large Synchronous Generators", currently under review by IEEE Transactions on Power Delivery.

A
METHODS TO COMPUTE TRANSFER COEEFICIENT

A *flicker transfer coefficient* between two busses in a network (e.g. A and B) 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 Eq. A-1.

$$T_{A \to B} = \frac{P_{stB}}{P_{stA}} \qquad \textbf{Eq. A-1}$$

where,

$T_{A \bullet B}$ 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.

It is important to recognize that the P_{st} values shown in Eq. A-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.

When synchronous flicker measurements are unavailable, $T_{A \to B}$ can be estimated using the various frequency domain calculation methods that are provided in [3] and [15]. These methods are presented as follows.

Since P_{st} values are related to fluctuations in *rms* voltage, Eq. A-1 can be shown to be equivalent to Eq. A-2 where V is the change in voltage at a particular bus.

$$T_{A \to B} = \frac{P_{stB}}{P_{stA}} \approx \frac{\left(\frac{\Delta V_B}{V_B}\right)_{RMS}}{\left(\frac{\Delta V_A}{V_A}\right)_{RMS}} \qquad \textbf{Eq. A-2}$$

Eq. A-2 can be readily solved using traditional short circuit calculation techniques. If Bus A is assumed to be the PCC of the disturbing load, the transfer coefficient from Bus A to Bus B can be determined by: 1) applying a three-phase fault at Bus A and 2) 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., Eq. A-2 can be reduced to Eq. A-3.

$$T_{A \rightarrow B} \approx 1 - \overline{V}_{B3\phi} \qquad \textbf{Eq. A-3}$$

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 Eq. A-3 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 station. 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 [16].

Similarly, the flicker transfer coefficient between two busses, A and B, in a network can be found using Eq. A-4.

$$T_{A \rightarrow B} = \left| \frac{\overline{Z}_{BA}}{\overline{Z}_{AA}} \right| \qquad \textbf{Eq. A-4}$$

where,

$\overline{Z}_{AA}$ is the complex driving point impedance at Bus A (p.u.), and

$\overline{Z}_{BA}$ is the complex transfer impedance between Bus A and Bus B (p.u.).

As before, both $\overline{Z}_{BA}$ and $\overline{Z}_{AA}$ can be found using traditional short circuit methods.

B
AUTOMATED FLICKER REPORT

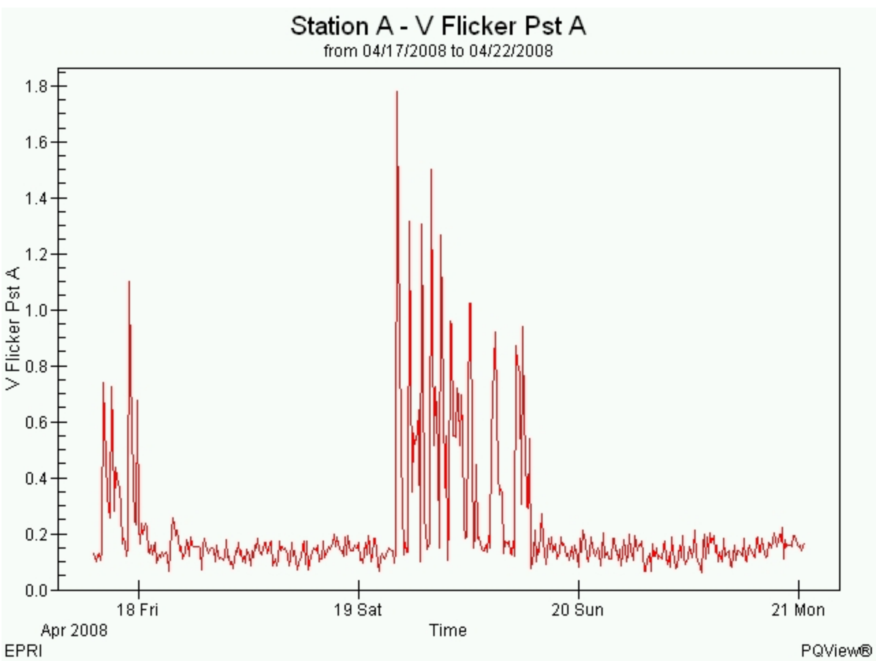
Report Details

Reporting Period: 04/18/2008 – 04/21/2008

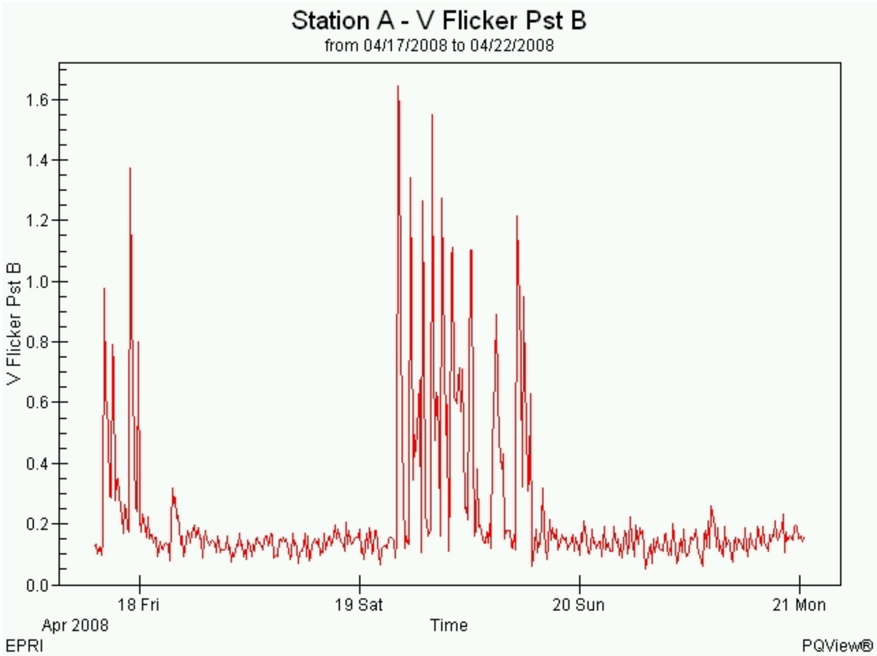
Meter Make:

Measurement Location: Station A

Bus Rated Voltage (kV): 138



Interactive Trend | Trend Table | Histogram | Interactive Histogram | Histogram Table | Profile | Interactive Profile | Profile Table



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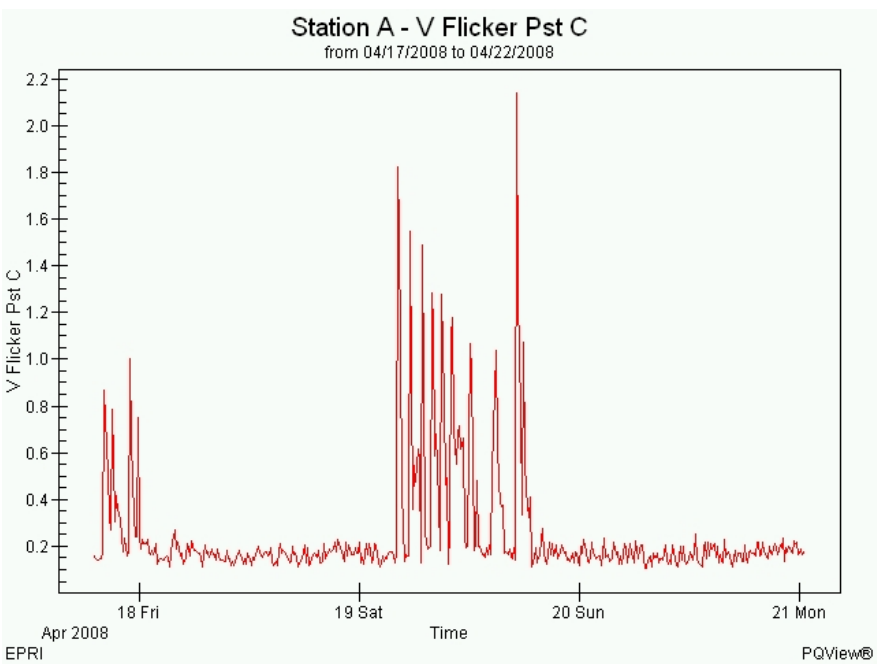

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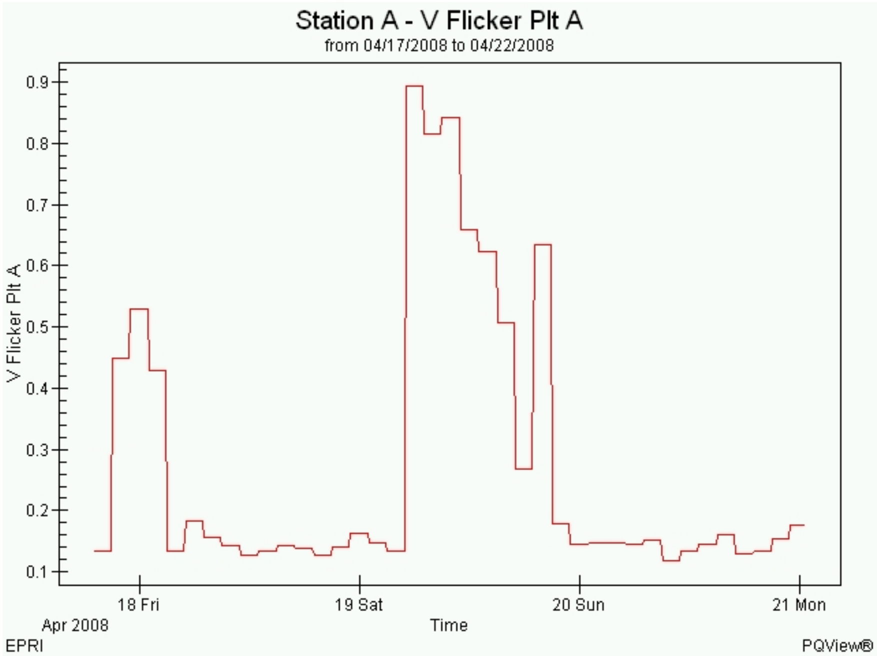

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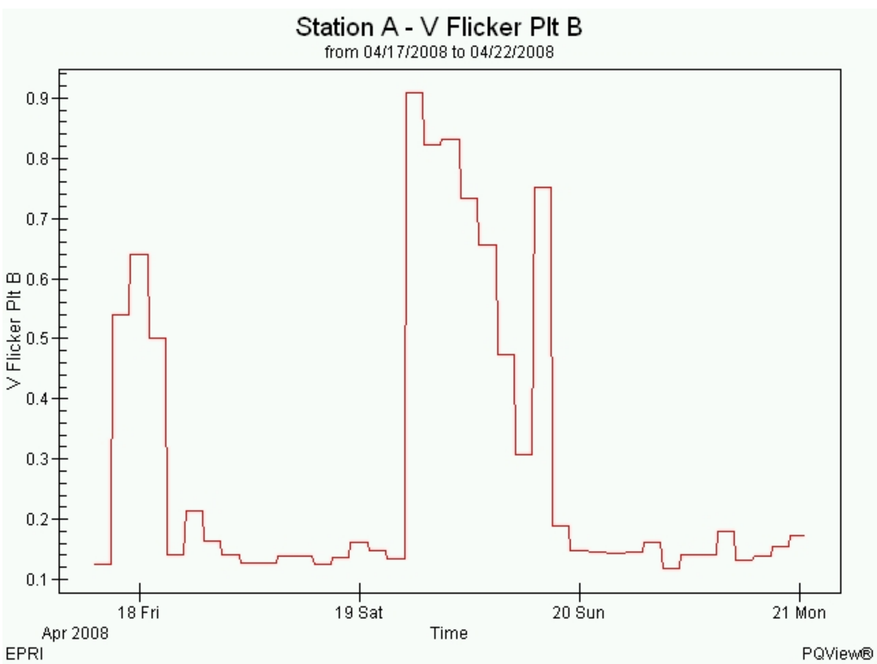

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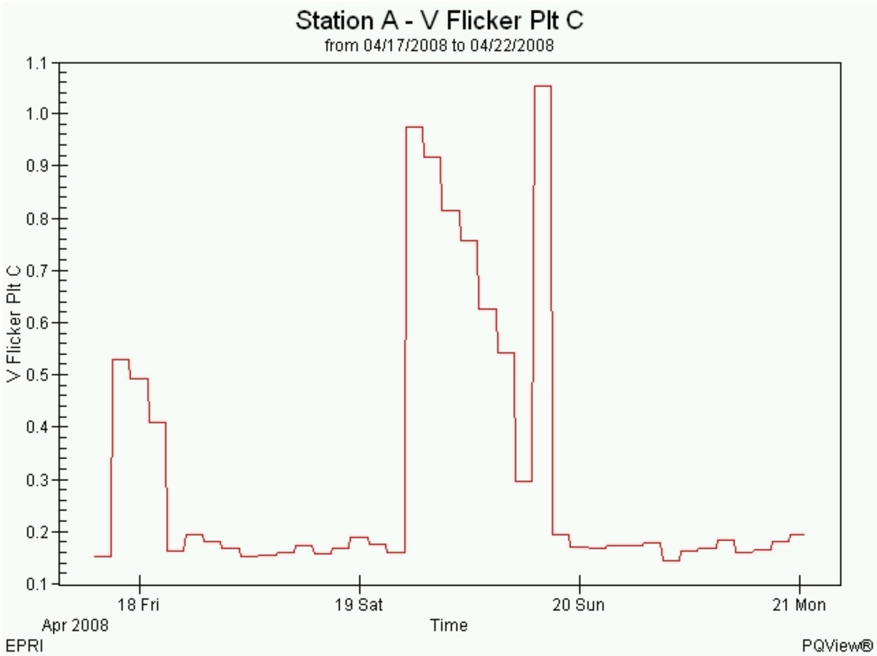

Interactive Trend | Trend Table | Histogram | Interactive Histogram | Histogram Table | Profile | Interactive Profile | Profile Table

Summary Table

Phase	Pst95	Pst99	Plt95	Plt99
A	0.726	1.265	0.842	0.894
B	0.759	1.342	0.832	0.909
C	0.753	1.486	0.973	1.053

Alarms

Pst99 level is greater than 0.9
Plt99 level is greater than 0.7

C

SAMPLE CALCULATIONS FOR LOW BACKGROUND FLICKER CASE

Let's assume that the limit for the acceptable level of flicker at the PCC for a new customer is set at

$$E_{Pst} = 0.8$$

Then we measure the background levels of flicker (99th percentile) before connecting the customer (this should be done over at least a two week period) and we get

$$P_{stbackground} = 0.4$$

Finally we measure the actual levels of flicker after connecting the customer and we get

$$P_{stactual} = 0.9$$

The flicker being caused by the new customer can be estimated by assuming the flicker levels add by a cubic summation.

$$P_{stactual} = \sqrt[3]{P_{stcustomer}^3 + P_{stbackground}^3}$$

Then

$$P_{stcustomer} = \sqrt[3]{P_{stactual}^3 - P_{stbackground}^3} = 0.87$$

This is the estimate for the flicker being caused by the customer at this PCC. In this case $P_{stcustomer}$ is found to be exceeding E_{Pst}

D

ARC FURNACE EVALUATION CIRCUIT BASE CASE MODEL PARAMETERS

- PCC Equivalent
  - Rated Voltage (rms): 138 kV (phase-phase)
  - Actual Voltage (rms): 138 kV (phase-phase)
  - Zero Sequence Resistance: 1.55 % @ 100 MVA
  - Zero Sequence Reactance: 7.05 % @ 100 MVA (60 Hz)
  - Positive Sequence Resistance: 0.98 % @ 100 MVA
  - Positive Sequence Reactance: 4.4 % @ 100 MVA (60 HZ)
- Main Transformer
  - Nominal power: 45 MVA
  - Nominal frequency: 60 Hz
  - Winding 1 Voltage: 138 kV RMSLL
  - Winding 2 Voltage: 13.8 kV RMSLL
  - Winding R: 0.007 pu
  - Winding X: 0.0739 pu
  - Winding impedance on winding 1: 0.9
- Series Reactor
  - Inductance (Full): 4.5 mH
  - Tap: 0 %
- Furnace Transformer
  - Nominal power: 35 MVA
  - Nominal frequency: 60 Hz
  - Winding 1 Voltage: 13.8 kV RMSLL
  - Winding 2 Voltage: 0.621 kV RMSLL
  - Winding R: 0.002 pu
  - Winding X: 0.02 pu

- Winding impedance on winding 1: 0.9

* Secondary Impedances
  - Resistance: 0.4 mOhm
  - Reactance: 2.5 mOhm
* PF Correction Bank1
  - Bank Type: Filter bank
  - Rating: 12 MVAR
  - Rated Voltage: 13.8 kV(phase-to-phase)
  - Tuning harmonic: 3.6 pu
  - Configuration: wye
  - Grounded: No
  - Connected: Yes
* PF Correction Bank2
  - Bank Type: Filter bank
  - Rating: 18 MVAR
  - Rated Voltage: 13.8 kV(phase-to-phase)
  - Tuning harmonic: 3.8765 pu
  - Configuration: wye
  - Grounded: No
  - Connected: Yes
* PF Correction Bank3
  - Bank Type: Filter bank
  - Rating: 10 MVAR
  - Rated Voltage: 13.8 kV(phase-to-phase)
  - Tuning harmonic: 4.892 pu
  - Configuration: wye
  - Grounded: No
  - Connected: Yes
* Arc Furnace
  - Minimum limit for arc resistance (Rmin): 0.0003 ohms
  - Maximum limit for arc resistance (Rmax): 0.009 ohms
* SVC
  - Bus voltage: 13.8 kV (phase-to-phase)

- TCR Rating: 50000 KVAR
- Kp: 15
- Ki: 2600
- Droop: 0.03 pu
- Connected: Unchecked

E
MOTOR STARTING EVALUATION BASE CASE PARAMETERS

Base Case Model Parameters

- Source Equivalent
  - Rated Voltage (rms): 115 kV (phase-phase)
  - Actual Voltage (rms): 115 kV (phase-phase)
  - Positive Sequence Resistance: 0.5 % @ 100 MVA
  - Positive Sequence Reactance: 10% @ 100 MVA (60 Hz)
- Supply Feeder
  - Descriptor: Manual Entry
  - Length (miles): 1
  - Resistance: 0.155 ohms/mile
  - Reactance: 1.555 ohms/mile
- Supply Feeder Series Cap
  - Bank Impedance: 2.5 ohms
  - Connected: No
- Step-down Transformer
  - Nominal power: 150 MVA
  - Nominal frequency: 60 Hz
  - Winding 1 Voltage: 115 kV RMSLL
  - Winding 2 Voltage: 6.6 kV RMSLL
  - Winding R: 0.005 pu
  - Winding X: 0.1 pu
  - Winding impedance on winding1: 0.9
- Customer Feeder
  - Descriptor: Manual Entry

    - Length (Feet): 1000
    - Resistance: 0.00023 ohms/1000 ft
    - Reactance: 0.0023 ohms/1000 ft
- Customer Feeder Series Cap
    - Bank Impedance: 1 ohms
    - Connected: No
- Customer Load
    - Load rating: 0.001 MVA
    - Voltage rating (RMS): 6.6 kV
    - Power factor: 0.9
    - Lagging: Checked
- Customer Bank
    - Bank Type: Cap bank
    - Bank rating: 10000 kVAR
    - Rated voltage: 6.6 kV (phase-to-phase)
    - Bank configuration: Delta
    - Grounded: Unchecked
    - Connected: Unchecked
- Starter
    - Option: Direct-on-line starter
    - Closing Instant: 11 seconds
- Starting Bank
    - Bank rating: 50000 kVAR
    - Rated voltage: 6.6 kV (phase-to-phase)
    - Overvoltage Setting: 1.03 pu
    - Connected: Unchecked
- SVC
    - Bus voltage: 6.6 kV (phase-to-phase)
    - Fixed Cap Rating: 130000 KVAR
    - TCR Rating: 130000 KVAR
    - Kp: 15
    - Ki: 2600
    - Droop: 0.03 pu

  - Connected: Unchecked
- Motor
  - Main Data tab
    - Rated Power: 11000 KVA
    - Rated line-to-line Voltage : 6.6 kVRMSLL
    - Frequency: 60 Hz
    - Number of poles: 4
    - Armature winding connection: Wye grounded
  - Electrical data tab
    - Rotor type: Double squirell cage
    - Rs: 0.018 pu
    - Lls: 0.015 pu
    - Lmd: 2.68 pu
    - Lmq: 2.68 pu
    - Rr1: 0.0162 pu
    - Llr1: 0.05 pu
    - Rr2: 0.117 pu
    - Llr2: 0.117 pu
  - Mechanical data tab
    - Lock rotor for negative speed: checked
    - Number of masses: 1
    - Index of rotor mass: 1
    - Moment of inertia: 2010
    - Speed deviation damping: 0
    - Absolute speed damping: 0
    - Use inertia constant H(s) instead of Moment of Inertia: Unchecked
- Mechanical Load
  - Mechanical Load: 100% Load torque, No breakaway torque
- Flickermeter Selection (For “Compute Pst” option)
  - Number of repetitions in 10 min period : 1
  - Simulation Duration (seconds): 20
  - Number of meters to process: 3
  - Flickermeter1 Name: Flickermeter_Source

- Flickermeter2 Name: Flickermeter_Customer
- Flickermeter3 Name: Flickermeter_Motor

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