ELECTRIC POWER RESEARCH INSTITUTE

PQ TechWatch

A product of the EPRI Power Quality Knowledge program

Issues, Techniques, and Standards **for Measuring Flicker**

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Contents

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EXECUTIVE SUMMARY

Sensitivity curves that were used for voltage fluctuation and flicker compliance have been found to be unsuitable for most modern flicker sources (e.g., arc furnaces), because these curves assumed standard square wave modulation and failed to take into account the variations over a period of time. One such method (the equivalent 10 Hz method) is still officially used in some Asian countries, but even this method has known issues with accuracy. Most utilities are now using Institute of Electrical and Electronics Engineers Standard 1453 that has fully adopted International Electrotechnical Commission Standard 61000-4-15, for measuring flicker, and recently IEC Standard 61000-3-7, for assessment of limits for fluctuating loads. Adoption of this standard has helped standardize monitoring equipment for flicker and application of its limits throughout the world.

This PQ *TechWatch* gives a history of voltage flicker and the attempts that have been made to measure it. It looks at the IEC flicker measurement and assessment methodology and investigates issues around its use and attempts to improve it. For example, the IEC flicker meter is not presently suitable for modern lighting technologies, is unable to quantify flicker contribution of any single source in comparison to background flicker, and has been found incapable of accurately detecting flicker due to interharmonics any higher than the 2nd harmonic frequency.

A case study provides further information about flicker measurements. That investigation sought to identify and quantify the individual flicker contributions from the various 13.2-kV feeders from a substation bus. Solutions for mitigation are discussed.

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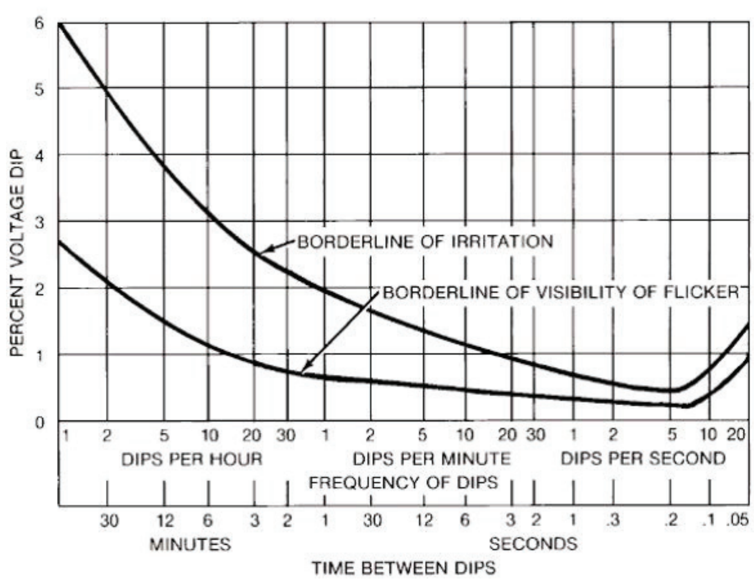
INTRODUCTION

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. These fluctuations can be caused by disturbances introduced during power generation, transmission, or distribution but are typically caused by fluctuations in power demands of large variable loads. 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. Therefore, individual or a combination of corrective actions are typically needed if end customers start complaining about objectionable flicker in their lamps.

To address such problems, after the beginning of the 20th century, many companies developed curves to represent the severity of flicker through tests on human subjects. One such set of curves developed by General Electric, and later modified and published by the Institute of Electrical and Electronics Engineers (IEEE) in Standard 141-1993 and Standard 519-1992, is shown in the figure below. 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 seven to eight dips per second. 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 root-mean-squared (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 volt-ampere reactive (VAR) compensation for flicker control of seam welders and inability to address multiple dosage issues.[1] Despite these drawbacks, these curves may still be used by a few electric utilities as a tool for imposing flicker limits on industrial customers connected to the grid.

Example of a Flicker Sensitivity Curve

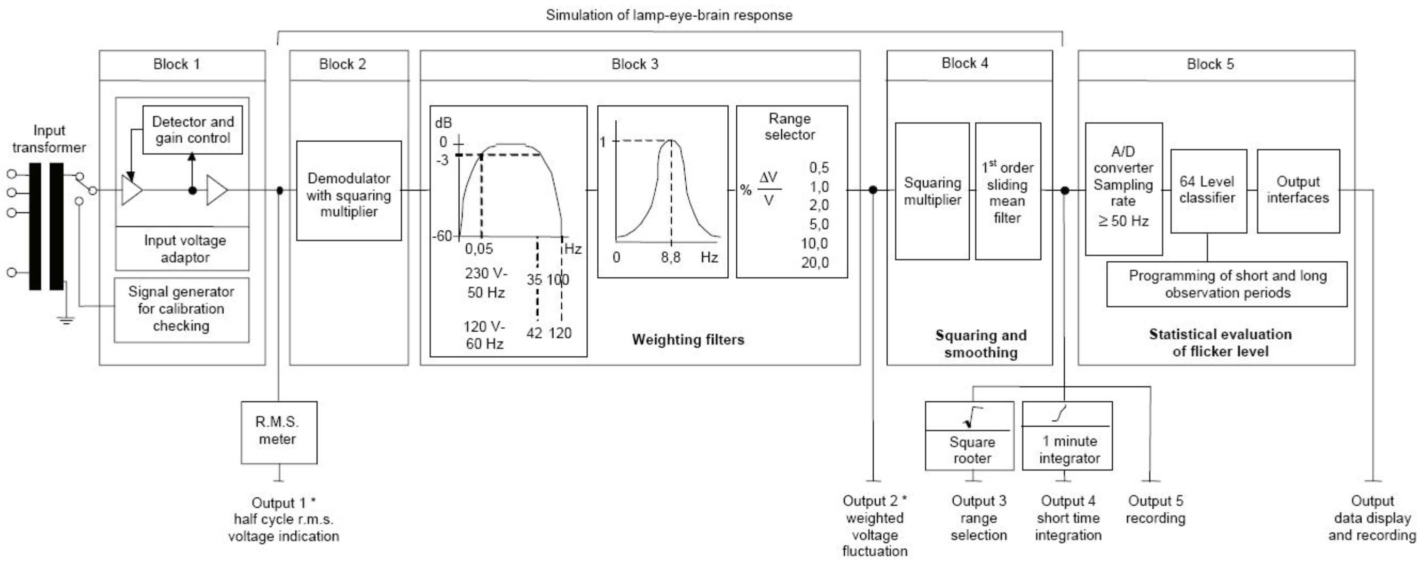


Source: IEEE Standard 141-1993 and Standard 519-1992

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 1453-2004.[2] This method has been adopted from International Electrotechnical Commission (IEC) Standard 61000-4-15.[3] 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. The figure on the top of the next page shows a block diagram of the flicker meter. Short descriptions of the individual blocks are given here.

Functional Block Diagram for the IEC Flicker Meter



Source: IEEE Standard 1453-2004

Flicker monitoring has been standardized in the United States using a meter that is completely described in IEEE Standard 1453-2004.

Block 1. 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 upon the input carrier voltage level.

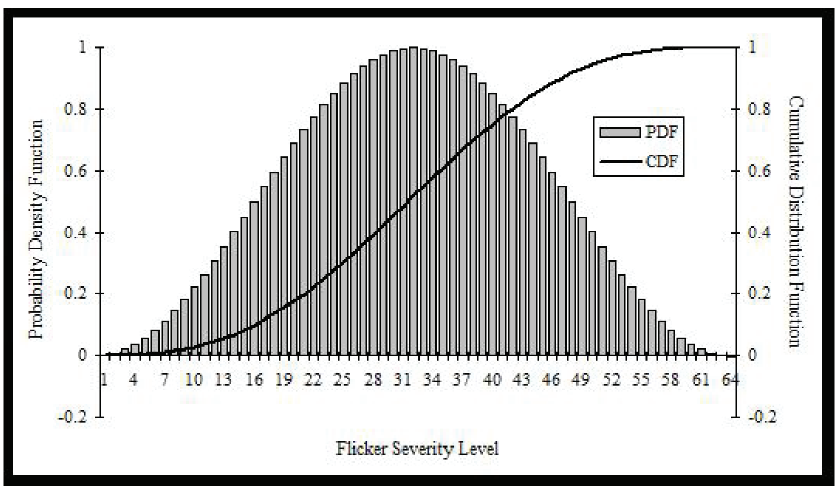
Block 2. Block 2 is simply a squaring demodulator that squares the input to separate the low frequency (0.5–30 Hz) voltage fluctuation (modulating signal) from the main voltage signal (carrier signal), thus simulating the behavior of the incandescent lamp.

Block 3. Block 3 consists of multiple filters that 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. Block 4 consists of a squaring multiplier and sliding mean filter. The voltage signal is squared to simulate the nonlinear 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.

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

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, is based upon an observation period of 10 minutes. This period is based upon assessing disturbances with a short duty-cycle or those that produce continuous fluctuations. P_{st} can be found using the following equation:

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

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 the equations below:

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

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

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

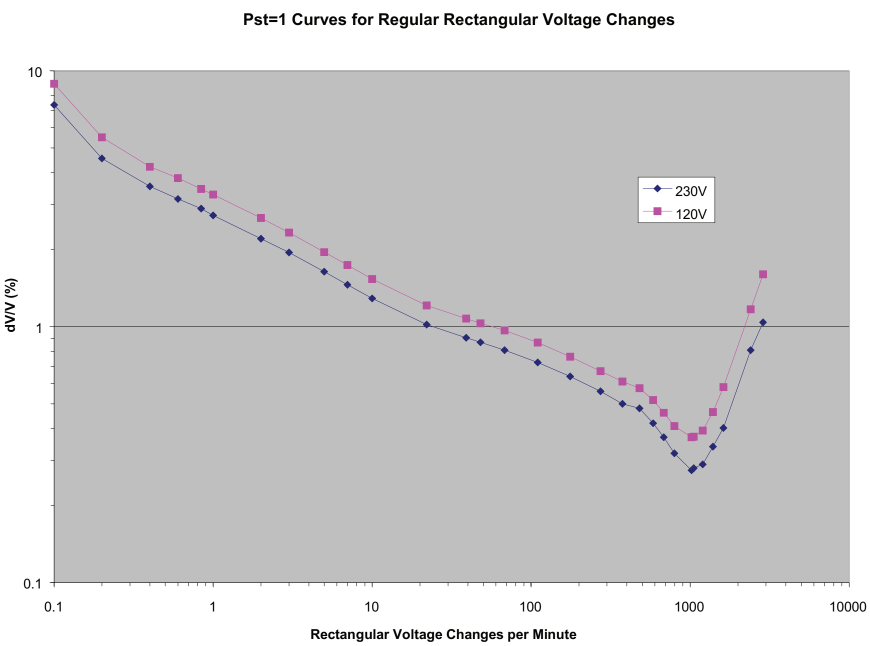
$$P_{50s} = \frac{P_{30} + P_{50} + P_{80}}{3}$$

The long-term flicker severity, P_{lt}, is calculated from twelve successive P_{st} values using the equation

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

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 lightbulb 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 wattage 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 the figure below.

Comparison of 120V and 230V Weighting Curves for Flicker-Meter Calculations



Source: IEC Standard 61000-4-15

The flicker performance of CFL and LED lamps is not consistent across different samples and is thus difficult to standardize, unlike that of the incandescent lamp.

ISSUES WITH IEC FLICKER METER

The IEC flicker meter is most widely used to quantify flicker, but even this approach has some known issues. These are addressed in this section.

Flicker Performance of Modern Lamps

To start with, the existing IEC flicker meter is designed and calibrated based on the flicker performance of general-purpose incandescent lamps. However, due to their significant energy-saving potentials, energy-efficient lamps such as compact fluorescent lamps (CFLs) and light emitting diode (LED) lamps are being promoted by many utilities worldwide, and some countries and states even have regulations in place for mandatory replacement of all incandescent lamps. Research so far has indicated significantly less susceptibility of modern (nonincandescent) lighting to voltage fluctuations at full power in terms of corresponding changes in light output.[4] Use of different weighting filters in Block 3 of the flicker meter has been suggested to adapt it for other lamp types such as CFLs and LED lamps.[5] Despite their merits, such suggestions have not found their way into the industry standards as of now, perhaps because lighting technology is constantly evolving and the flicker performance of CFL and LED lamps is not consistent across different samples and is thus difficult to standardize, unlike that of the incandescent lamp.

In addition to the evidence pointing to better flicker performance of modern lighting, recent work has found a lack of correlation between measured flicker levels and network user complaints. Consequently, International Council on Large Electric Systems (CIGRE) Working Group (WG) C4.111 has been looking into the possibility of revising low-voltage (LV) and medium-voltage (MV) compatibility levels with regard to voltage fluctuations. The group has been assigned five tasks:

- Document existing work dealing with susceptibility of modern lighting technologies with regard to voltage fluctuations.
- Document existing work dealing with susceptibility of other (nonlighting) user equipment with regard to voltage fluctuations.
- Evaluate the potential for suggesting modifications to the IEC 61000-4-15 flicker meter so that the traditional output value and level $P_{st} = 1$ can continue to serve as a measure of compatibility level.
- Recommend possible alternatives to the flicker-meter concept of P_{st} for specifying,

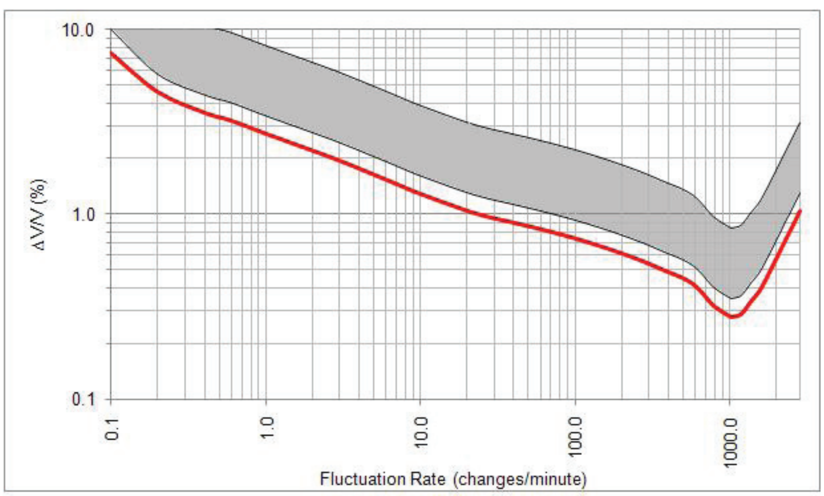
A majority of responders to a 2011 questionnaire did not support a change in the Pst = 1 flicker curve at this time.

measuring, and assessing voltage fluctuations.

- Recommend areas where additional research is needed in order to further the objective of revising LV and MV compatibility levels with regard to voltage fluctuations.

As a part of this effort, a questionnaire was prepared in 2011 and circulated among the interested equipment manufacturers, network owner/operators, and stakeholders, including the members of IEC SC77A WG1, WG2, and WG8 and the members of IEEE Flicker Task Force. The participants were asked about expected (or known) impacts on the performance (or flicker immunity) of the equipment if the flicker curve were to be raised by between 1.25 and 3.0 times the existing flicker curve (as shown by the shaded area in the figure below).

Proposed Change to P_{st} = 1 Flicker Curve



This 230V Pst = 1 curve from IEC 61000-3-7 (2nd ed.) shows possible increases by factors between 1.25 and 3.

Source: CIGRE WG C4.111

The group has reported that 29 responses were received from 15 countries, and the overwhelming majority of the responders did not support a change in the P_{st} = 1 flicker curve at this time. Some of the more common reasons:

- The incandescent lamp on which the existing P_{st} = 1 flicker curve is based will continue to be used for many years to come on a global scale.
- Other equipment could be sensitive to voltage fluctuations that are less (smaller in magnitude) than the potential factor of 1.25–3 increase (based on the defining values for the P_{st} = 1 flicker curve) in permissible voltage fluctuation levels.
- A single new reference as replacement for the incandescent lamp is unlikely to be acceptable to all the stakeholders.

The above questionnaire represents only one component of the information that has been gathered by CIGRE WG C4.111. It is continuing to thoroughly review the research that has been performed to date in this area and is expected to make final recommendations on the issue in 2013. EPRI has recently performed detailed testing to evaluate the flicker performance of modern lighting under varying system conditions.[6] In the case of dimmable lighting technologies, the dimmer operation to reduce the lamp brightness level was invariably found to increase the flicker susceptibility of all the lamp types. In one instance, a CFL lamp was actually found to have worse flicker performance than incandescent lamps when operating at 50% brightness level. The evidence is especially strong to suggest worsening of the flicker performance of dimmable lamps when operating at reduced brightness levels. These test details will be shared with CIGRE WG C4.111 to aid in making informed decisions on the issue of potential revision of flicker limits.

Another key issue is the reported inaccuracies in flicker-meter response when the supply system is rich in interharmonics.

Impact of Interharmonics on Flicker

Superimposed interharmonics in a power system can lead to oscillating luminous flux and thus become a source of light flicker.[7] 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 the presence of an interharmonic, average luminous flux gets amplitude modulated as per the following:

$$f_M = |f_0 - f_{ih}|$$

where

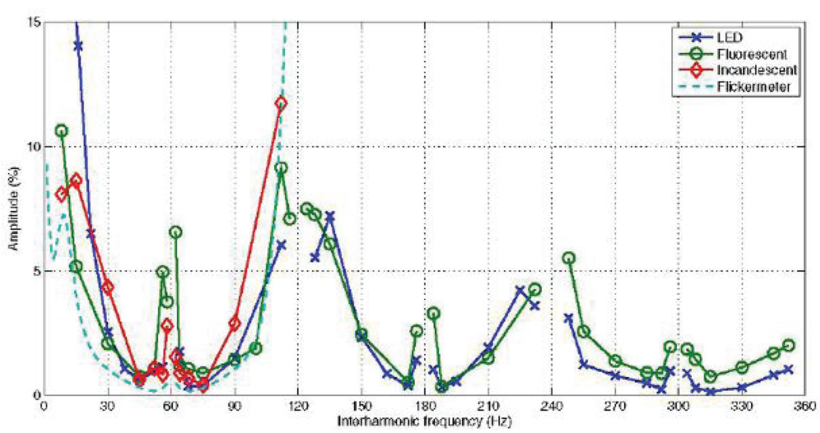
f_0 is fundamental frequency and

f_{ih} is interharmonic frequency.

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

IEC flicker meters in their existing form are not capable of accurately detecting flicker due to interharmonics.

Minimum Interharmonic Amplitude Generating Perceptible Flicker over a Frequency Range



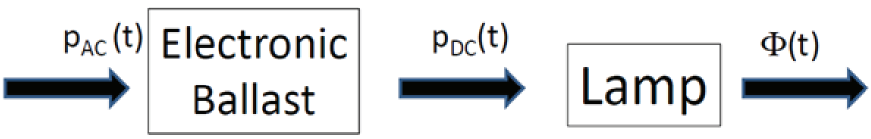
Source: T. Kim et al. [8]

Flicker performance of CFLs and LED lamps has been compared with those of incandescent lamps in the presence of interharmonics.[8] Experimental results (see sensitivity curves in the figure below) 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 a diode bridge rectifier in LED lamps and CFLs.

As mentioned before, computations in IEC-compliant flicker meters are based on the measurement of fluctuations in RMS supply voltage, which means these meters are capable of detecting only that flicker caused by low-frequency interharmonics (below $2f_0$) as higher order interharmonics do not cause much RMS variation. As a result, the existing version of flicker meters is 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 a cut-off frequency of 42 Hz for the bandpass filter in Block 3 of the flicker meter. Based on these observations, the conclusion is that IEC flicker meters in their existing form are not capable of accurately detecting flicker due to interharmonics.

Ongoing research focuses on potential modification of the flicker meter so that it can take into account interharmonics at frequencies higher than 2nd harmonic. One such work is looking at developing a generalized lamp model that is suitable for both incandescents and modern lighting technologies such as CFL and LED lamps.[9] The majority of modern lamp technologies make use of an electronic ballast that employs a switch-mode type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. The key components of the conversion of the input electrical power to luminous flux in the lamp are shown in the figure below.

Conversion of Input Power to Luminous Flux in Most Modern Lamps

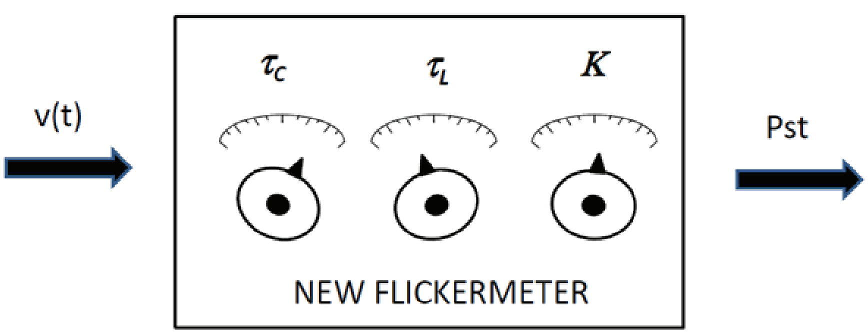


Source: J. Slezingr et al. [9]

The electrical circuit behavior of such lamps has been modeled using a simplified model that represents a simple rectifier, with filter capacitor, supplying a resistive load. Such a model can be defined using the following three parameters:

- The time constant of the DC load, τ_C, can be assumed as almost invariant for specific types of lamps. Its value for the CFLs is in the range of 10 to 70 ms, with an average value of 30 ms.

New Flicker Meter Based on Generalized Lamp Model



Source: J. Slezingr et al. [9]

- The lamp time constant τ_L takes into account the inertia (dynamics) of lamp discharge and the quantum lag of radiant pass in phosphor coating. It depends on the type of phosphors and their mixing to get output light of specific color, and it is in the range from 3 to 10 ms with average value of 4.5 ms.
- *K* is the power of fitting function representing overall gain of the CFL. The K value of typical CFL with built-in electronic ballast is in range from 0.7 to 1.4 with average of 0.9.

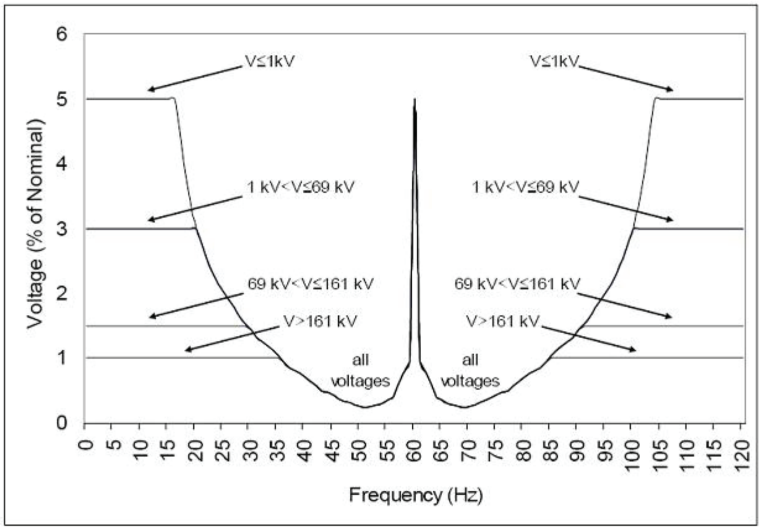
The above model can be used to represent a general-purpose incandescent lamp by specifying a value of 0.0 for τ_C and a value of 21.2 ms for τ_L. The concept drawing of the modified flicker meter based on this generalized lamp model is shown in the figure below at bottom right. This meter is expected to meet the dual objective of being able to take into account interharmonics at frequencies higher than 2nd harmonic in addition to being calibrated according to IEEE Standard 1453.

Meanwhile, the recommended solution to this problem of unsuitability of using the IEC flicker meter for flicker due to higher order interharmonics lies in using amplitude-only interharmonic limits that are presented in *IEEE Draft Guide for Applying Harmonic Limits on Power Systems* (see the figure on the following page.[10]

Quantifying Flicker Contribution of Individual Loads

The IEC flicker meter is constrained by the fact that it can only provide the overall flicker measurement at any single point on the system. The meter in its current form is unable to quantify flicker contribution of any single source in comparison to background flicker or flicker from other sources. For example, the flicker meter cannot quantify the individual flicker contribution of multiple arc furnaces that may be operating in the vicinity. To estimate

Voltage-Only Interharmonic Limits Based on Flicker in Revised IEEE Std. 519



Source: IEEE P519.1/D12 [10]

the flicker contribution of an individual source, the contribution of the background flicker in the system must be excluded. The underlying principle of one approach that has been successfully used is that the source 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. The procedure for the implementation of this approach is presented here (see figure below):

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. 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 were the only source of voltage fluctuations.

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

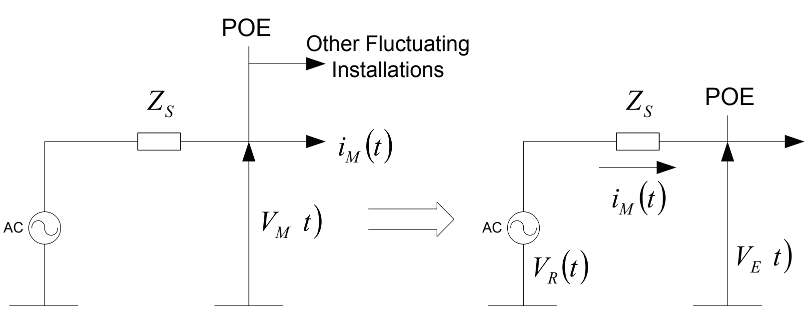
where $V_R(t)$ represents the voltage at the monitoring point if the system was unloaded and whose angle should be equal to that of the voltage waveform $V(t)$ computed using the following equation:

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

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

This concept was used to assess the flicker contribution of individual feeders at a substation.

Measurement-Based Approach for Estimating Flicker Contribution of Single Customer



Source: IEEE Standard 1453-2004

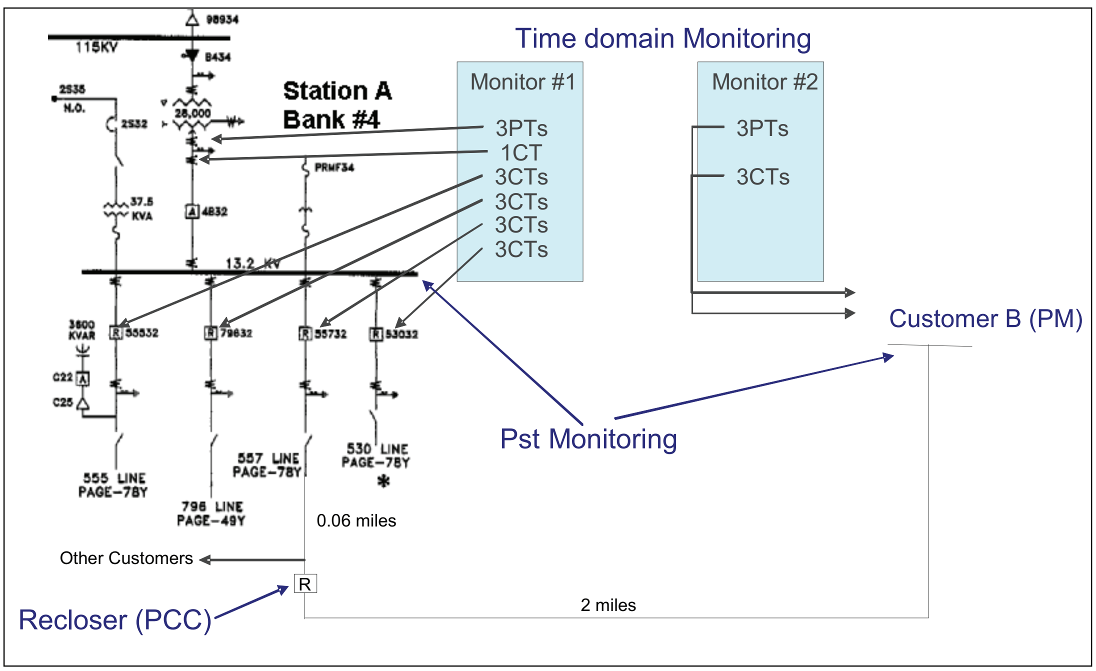
CASE STUDY: FLICKER ASSESSMENT OF SUBSTATION FEEDERS

A utility was receiving customer complaints regarding high flicker levels in the distribution system fed by its Substation A. The primary suspect was Customer B, comprising multiple resistive-spot-welding loads fed from one of the 13.2-kV feeders (Line 557) out of Substation A (see the figure below).

The primary goal of the study was to identify and quantify the individual flicker contributions from the various 13.2-kV feeders fed from the substation bus and identified as follows:

- Line 555
- Line 796
- Line 557
- Line 530

Single-Line Diagram of System and Measurement Setup



Flicker-Meter Measurements Analysis

The utility installed a power quality meter at the 13.2-kV bus of Substation A and at the primary metering point of Customer B. $P_{st99\%}$ values at the substation 13.2-kV bus and customer primary metering (computed for the four-week observation period) are shown in the table below. These flicker levels at the substation are exceeding the IEEE Standard 1453 recommended limits and can be expected to result in customer complaints.

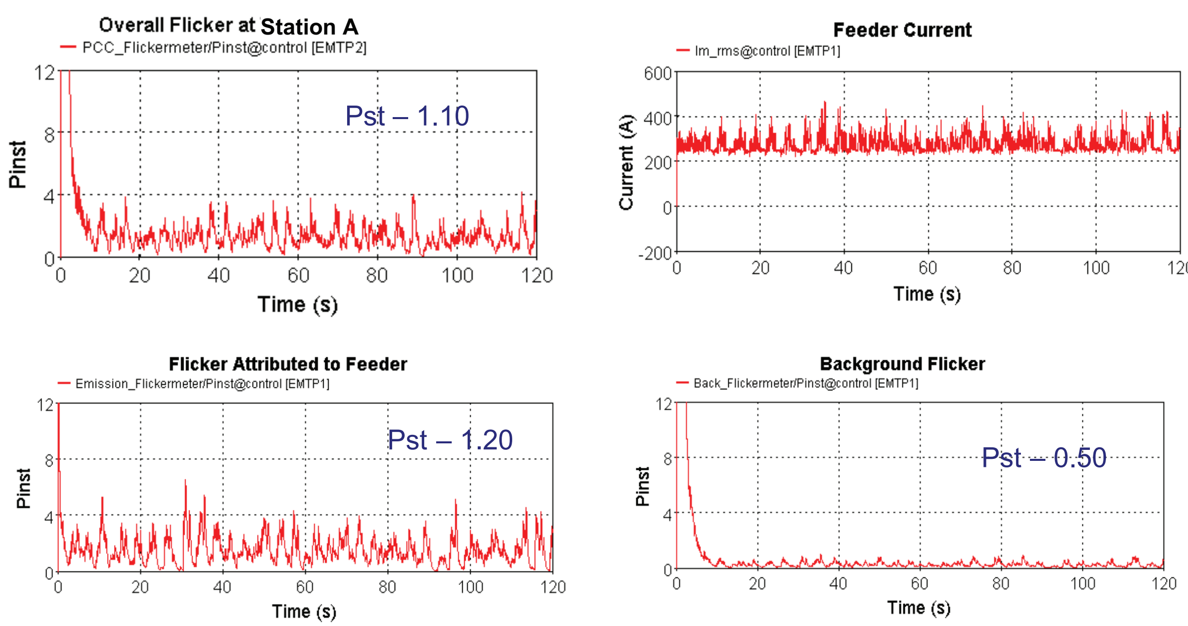
Current Injection Analysis

For the purpose of this analysis, a series of time-domain measurements were carried out both at substation and primary metering of the customer. The approach of correlating flicker contribution to the current variations was used on the measurement data to compute the flicker levels that can be attributed to individual feeders. Most of the overall flicker was determined to be attributable to Line 557 (see figure below). This can be explained by the significant variations in the current drawn by this feeder.

Flicker ($P_{st99\%}$) Levels

Location	$P_{st99\%}$
Substation 13.2-kV bus	1.23
Customer primary metering	4.27

Flicker Measurement Results for Feeder Line 557



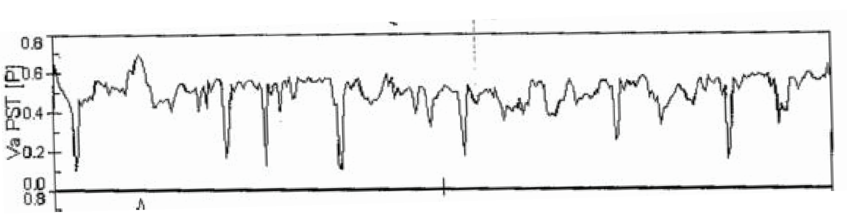
In this case study, it was evident from the magnitude and the trends of the time-domain data that almost the entire flicker at primary metering was being contributed by the customer.

The next step involved evaluating the contribution of the customer to the flicker levels in the utility system around the substation. The time-domain data captured at the customer's primary metering was used for the detailed analysis. It was evident from the magnitude and the trends that almost the entire flicker at primary metering was being contributed by the customer.

Solution

Based on these findings, the customer accepted the need for mitigation of flicker to acceptable levels. A static volt-ampere reactive (VAR) compensator system that was already in place was determined incapable of providing the necessary level of mitigation. The solution that was actually implemented was in the form of changes in process controls that would ramp the welding loads on and off instead of in step changes. As a result, flicker levels at the substation have gone down to acceptable levels as monitoring over a week found P_{st} to be mostly below a value of 0.6., as shown in the figure below.

Flicker Measurement at Substation After Solution Implementation



EQUIVALENT 10-HZ VOLTAGE FLICKER MEASUREMENT (ΔV_{10})

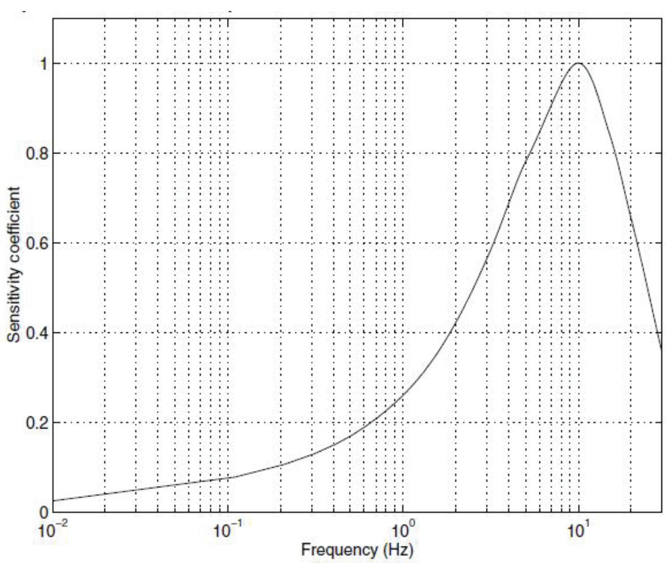
The alternate measurement approach that is used in several Asian countries is "Equivalent 10 Hz Voltage Flicker Measurement (ΔV_{10})." This methodology was developed by the Central Research Institute of the Electric Power Industry (CRIEPI) of Japan in 1978 and has been evaluated in a recent paper.[11]

This method requires calculations in frequency domain that involve performing fast Fourier transforms to extract components of various frequencies in supply voltage. The next step involves looking up the equivalent effect of individual frequency components with respect to 10 Hz by referring to the sensitivity coefficient curve in the figure on the following page. The sensitivity coefficient has a peak value of unity for a 10-Hz component. The final step involves computing a value of flicker severity factor, ΔV_{10}, by combining the individual sensitivity coefficients using the following equation:

$$\Delta V_{10} = \sqrt{\sum_{n=1}^{\infty} (a_n . \Delta V_n)^2}$$

where a_n is the sensitivity coefficient for n Hz frequency component in the figure, and ΔVn represents the corresponding amplitude of the voltage fluctuation. CRIEPI puts the limit of 0.45% as an acceptable value for ΔV_{10}.

Flicker Sensitivity Coefficient Curve



Source: Wang, Chen, and Yang [11]

Despite being most widely used, the IEC flicker measurement and assessment methodology still has some issues that the industry is trying to resolve.

The "Equivalent 10 Hz Voltage Flicker Measurement (ΔV_{10})" method is somewhat easier to implement but is not as rigorous as the IEC method presented earlier in this document. Concerns have been raised regarding the accuracy of this methodology as this method might overestimate flicker contribution due to variations at higher frequency (above 20 Hz) and underestimate the flicker contributions due to variations at lower frequency (below 0.1 Hz).[12] Further, the method has not been updated since it was introduced to take into account the complex nature of newer loads.

CONCLUSION

Historically, various sensitivity curves that were developed subjectively by carrying out tests on human subjects were used for voltage fluctuation and flicker compliance. However, those curves were found to be unsuitable for most modern flicker sources, like arc furnaces, because these curves assumed standard square wave modulation and failed to take into account the variations over a period of time. One such method (the equivalent 10 Hz method) is still officially used in some Asian countries, but even this method has known issues with accuracy.

The majority of electric utilities have now adopted IEEE Standard 1453 for evaluating flicker levels and implementing limits for customers that cause voltage fluctuations. This standard has fully adopted IEC Standard 61000-4-15 (formerly IEC Standard 868) for measuring flicker, which is based on years of combined research by engineers and scientists in the areas of the human ocular system, brain reaction, and lamp response. Adoption of this standard has helped standardize monitoring equipment for flicker throughout the world. Recently, IEEE Standard 1453.1-2012 has also fully adopted IEC Standard 61000-3-7 to avoid any ambiguities in applying limits for customers.[13]

Despite being most widely used, the IEC flicker measurement and assessment methodology still has some issues that the industry is trying to resolve. The IEC flicker meter is designed and calibrated for general-purpose incandescent lamps and thus is not suitable for modern lighting technologies like CFL and LED lamps that are generally believed to be less prone to flicker. Recommended flicker compatibility and planning levels are also believed to be too conservative, as evident from less-than-expected instances of customer complaints based on the magnitudes of the recorded flicker levels. Additionally, the IEC flicker meter in its existing form has been found incapable of accurately detecting flicker due to interharmonics at frequencies higher than that of the 2nd harmonic.

NOTES

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