PQ Encyclopedia
A product of the EPRI Power Quality Knowledge-Based Services program

EPRI ELECTRIC POWER RESEARCH INSTITUTE



Understanding Voltage Flicker

Chapter 6

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Doni Nastasi, EPRI
Philip Keebler, EPRI
Bill Howe, EPRI

Flicker is undesired fluctuation in luminosity from lighting fixtures resulting from variations (modulation) in the levels of supply voltage. Although it is the lighting level that is actually "flickering," the shorthand notation of "voltage flicker" is often used to describe the linked phenomena of voltage vagaries precipitating noticeable changes in light levels.

Voltage flicker is somewhat unusual in the power quality (PQ) world: Although special instruments may be needed to precisely quantify the level of flicker, no tools are needed for initial detection — it is readily observed by the unaided eye in lighting levels. And, although many PQ phenomena, once detected, have straightforward solutions, this is generally not the case for flicker problems. Finally, again unlike most other PQ phenomena, flicker seldom causes process interruptions or equipment damage. Rather it is an annoyance and hindrance to workplace productivity.

This chapter provides insights on what flicker is, what are the most common causes, how to measure it, and how to approach mitigation.

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INTRODUCTION

Imagine you are in a quiet room reading a book when an air conditioner comes on. You may notice an electric lamp flicker, but the brief episode probably won't concern or annoy you. Now imagine you are reading in that room while the disturbance is being generated outside the home — perhaps by a nearby scrap iron melting facility that runs in production mode around the clock. With the light flickering more frequently, you are much more likely to become irritated.

Lighting has a high sensitivity to voltage variations.

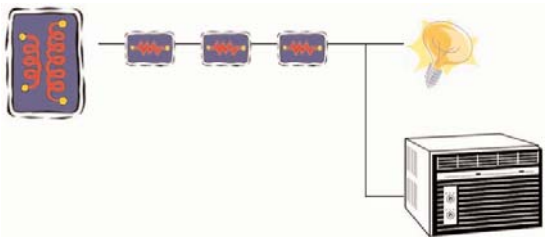
Lighting has a high sensitivity to voltage variations. Fluctuations in the root mean square (RMS) voltage of only 0.25% are sufficient to cause noticeable flicker in lightbulbs. The sensitivity is dependent on the frequency and magnitude of the voltage fluctuations. The term *flicker* usually refers to the light fluctuations that occur with the varying voltage to a lightbulb or to the voltage fluctuations themselves. International standards have been developed for characterizing the voltage fluctuations based on the potential effects on lighting and the human perception of the lighting variations.

In many small towns originally built around an industry, the power system built primarily for the plant is now feeding a portion of the community. Those who share the circuit with the plant are exposed to problems of fluctuating voltage or flicker. In steel mills, welding facilities, and arc furnaces, for example, the equipment draws power from the electric utility grid in irregular pulses of very high magnitude. These pulsed currents cause sudden voltage drops, which affect large portions of the distribution circuit and, therefore, affect a large number of homes and businesses within the community.

Why Lights Flicker

Light flicker is often caused by otherwise minor fluctuations in voltage — often as little as 2% variation.[1] These small voltage fluctuations are harmless and do not interrupt operation of any electrical appliances; however, they can manifest as visible light flicker, particularly evident in incandescent lighting and lights on dimmer switches. As a simple example, consider the circuit shown in the figure below. An observer might notice that when the air conditioner turns on, it causes the lightbulbs to flicker. The reason for the blink is a sudden voltage drop in the wiring. The voltage drop typically produces a 2% to 4% reduction in RMS voltage and lasts for only a few cycles as the compressor motor starts.

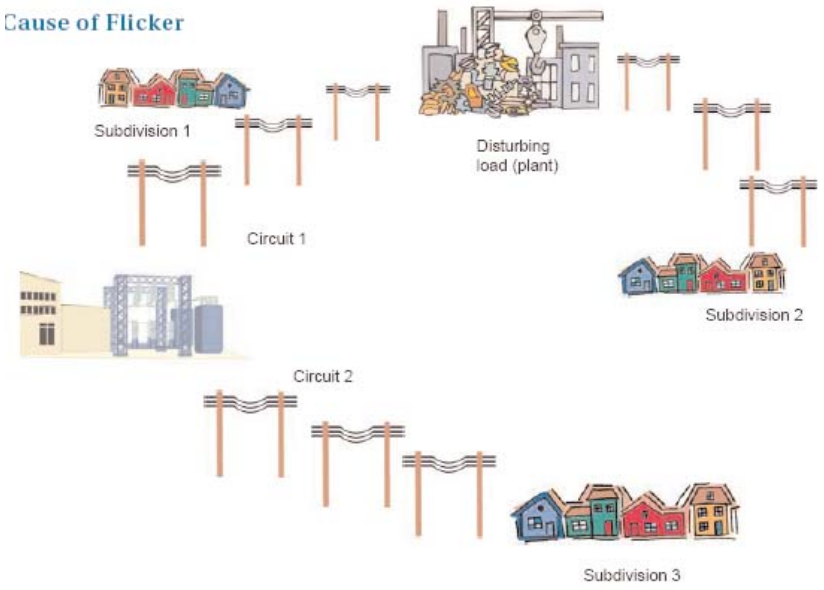
Voltage Drops in the Wiring Cause Light Flicker



Electrical wiring in residential, commercial, and industrial settings is required to be low resistance; however, as current moves through the resistance in wiring, there are small but sometimes significant drops in voltage. For example, typical 12 AWG residential wiring has a resistance of only 0.0016 Ω/ft. However, when an end-use device, like an air conditioner, first turns on, the abrupt change in current flow will cause a change in voltage drop across wiring and, therefore, cause a change in voltage at any nearby lamps.

The same circuit principles can apply on a larger scale to an entire distribution circuit. That scenario is depicted in the figure at the top of the next page. The steel melting facility's arc furnaces (disturbing load) draw current in pulses. These pulses, in turn,

Proximity to Industrial Loads Can Exacerbate Flicker



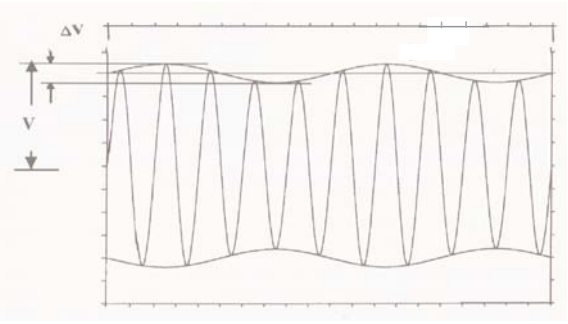
Electrical distribution systems have to supply a wide range of electrical loads, from residential appliances and personal computers to industrial arc furnaces and similar heavy loads. When the heavy loads are operating (circuit 1), flicker can affect other loads on the feeder or even on adjacent feeders coming from the same substation (circuit 2).

cause brief voltage fluctuations that affect the lights fed from the same distribution circuit. Subdivisions fed from the same circuit see different magnitudes of disturbance, depending on their proximity to the plant. Those closer to the plant and those downstream of the plant see the greatest magnitudes of voltage fluctuation. Those on a parallel circuit (circuit 2) can also see flicker if they are fed from the same transformer as the plant. Those closest to the substation and those fed from different transformers are least affected.

The characteristics of fluctuating line voltages can be described by discussing two basic characteristics of electric waveforms — the amplitude of the waveform and its spectral content. A fluctuating line voltage will have an amplitude that is changing in a low-frequency manner. This changing amplitude can also be described as an additional spectral component that becomes added to the fundamental power-line frequency — 60 Hz for U.S. (domestic) service territories and 50 or 60 Hz for international territories.

The figure below illustrates one example of a 60-Hz sine wave that contains a secondary spectral component that causes the normal amplitude to vary (or be modulated) in a low-frequency manner. We can see that adding this component to the nominal line voltage causes new maxima and minima along the waveform. The voltage at the maxima is higher than the amplitude of the nominal line voltage. And, the voltage at the minima is lower than the amplitude of the nominal line voltage. In other words, the added component "pulls up" the amplitude in one area above the nominal voltage of the waveform and "pushes down" the amplitude in an adjacent area below the nominal voltage. This "pulling" and "pushing" of the nominal amplitude is the resulting actual mathematical modulation. In other words, half of this modulating waveform (Δv/2) adds to the peak of the normal voltage and the other half subtracts from it. Thus, the net effect of having the secondary component added to the primary component is a 60-Hz waveform that has fluctuations. And, these fluctuations repeat with the frequency (i.e., 0.1 to 25 Hz) of the secondary, or modulation, component.

Example Voltage Fluctuation of a Nominal Waveform



An idealized fluctuating voltage waveform.

Source: Adapted from UIE Guide to Power Quality of Electrical Supply for Industrial Installations—Part V: Flicker and Voltage Fluctuations.

COMMON SOURCES OF VOLTAGE FLICKER

Arc furnaces often lead to flicker complaints depending on the point of common coupling (PCC) as well as the response of power system, lamp, and the person within the compass of the light. Some unique interharmonic (noninteger harmonic) arc furnace effects have been reported to cause unusual voltage fluctuation phenomena. These can involve harmonic beat frequencies or a repetitive shifting in the phase angle of the harmonics. These interactions have been reported to cause irritating flicker in certain fluorescent lighting systems. With construction of arc furnaces close to residential and commercial customers, it is important to understand flicker-causing phenomena.

A wide variety of end-use equipment can cause voltage fluctuations, including:

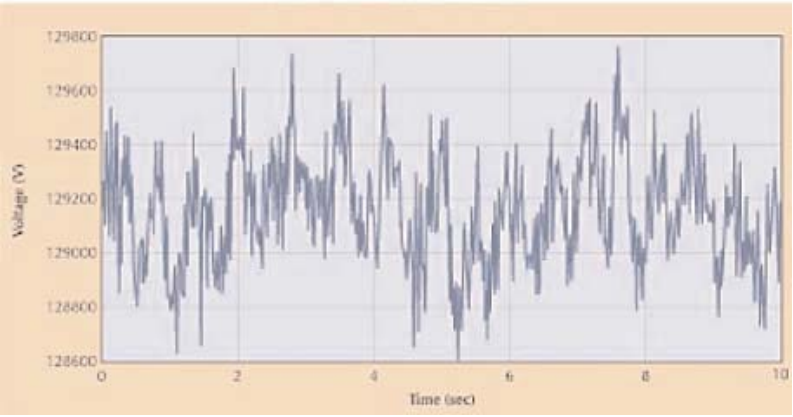
- Air-conditioning compressor motors
- Arc furnaces
- Arc welders (including spot welders)
- Electric boilers (large capacity)
- Heat-pump compressor motors
- Industrial motors (powering variable loads)
- Lasers
- Photocopying machines
- Power factor correction capacitors (switching operation)
- Presses (oscillating)
- Resistance welding machines
- Rock crushers
- Rolling mills
- Saw mills
- Tire testers
- X-ray machines

Loads that draw consistent levels of current generally do not cause voltage fluctuations.

Two general characteristics of each load are the size of the load in terms of its current requirement and its either one-step or pulsating current requirement. The current requirement in one-step loads are initially low and then almost instantaneously stepped up to a much higher value as the load comes on-line. These loads have the propensity to cause “one-shot” or noncyclic flicker. Noncyclic flicker can correspond to occasional voltage fluctuations such as that caused by the starting of a large motor. However, the current requirement for pulsating loads has a much greater effect on the utility power system in the load’s tendency to generate what can be periodic or nonperiodic changes in line voltage that are severe enough to create voltage flicker. Most pulsating loads generate cyclic flicker, which results from periodic voltage fluctuations such as those caused by the operation of a reciprocating compressor. The operation of a time-varying load, such as an electric arc furnace (see figure on the following page), may cause voltage flicker that can be categorized as a combination of cyclic and noncyclic flicker. This chapter provides some discussion on these sources of voltage fluctuations.

Steady-state operation of loads that draw consistent levels of current generally do not cause voltage fluctuations, but the switching on and off of large-capacity and some residential loads can. The switching on and off of one single large-capacity load such as an arc furnace can cause fluctuating voltages for a large number of customers connected to the same utility power system.

Voltage Flicker Caused by an Arc Furnace



Some loads, such as welders and arc furnaces, are notorious for causing prolonged periods of rapid changes in voltage.

Given a certain magnitude and duration of a single voltage fluctuation, one can predict the amount of light change that will occur. Institute of Electrical and Electronics Engineers (IEEE) Standard 1159, *Recommended Practice for Monitoring Electric Power Quality*, defined seven categories of voltage variations. These are transients, short-duration variations, long-duration variations, voltage imbalance, waveform distortion, voltage fluctuations, and power frequency variations. Electrical disturbance events are listed in the table on the following page in order of shortest to longest duration beginning with transients and ending with power frequency variations.

The categories of events called *voltage imbalance* and *waveform distortion* occur in the steady state; that is, they typically last longer than one minute up to a much longer time until the condition is resolved, if at all. Because voltage fluctuations are usually multicycle events of low frequency, they fall near the bottom of this list, near the long-duration events. Voltage fluctuations occur at frequencies less than 25 Hz and are generally intermittent in nature. On a per unit basis, voltage fluctuations can comprise 0.1% to as much as 7% of a nominal voltage waveform.

A graphical illustration of how voltage fluctuations are categorized on a voltage amplitude (magnitude) versus event duration plot helps to illustrate where fluctuations occur with respect to other common electrical disturbances, the nominal line voltage, and time (in seconds, minutes, hours, and cycles). The illustration at the top of page 6 shows this with respect to other voltage variations such as overvoltages, voltage dips (sags), short-duration variations, and long-duration variations.[2]

By the definition published in the IEEE Standard 1159, voltage fluctuations occur in two regions:

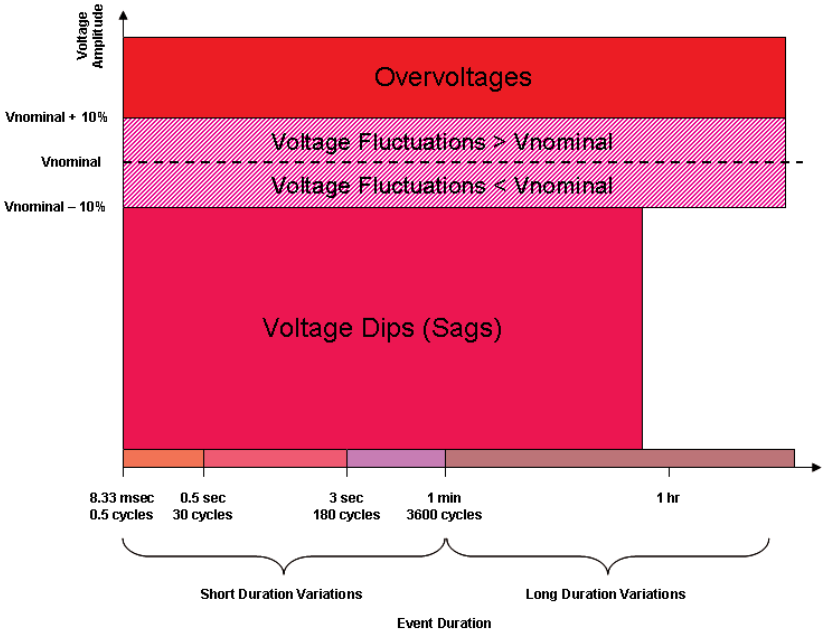
- between the nominal voltage and 10% above the nominal voltage, and
- between the nominal voltage and 10% below the nominal voltage.

IEEE Categories and Typical Characteristics of Power System Electromagnetic Phenomena

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 nsec rise	<50 nsec	
1.1.2 Microsecond	1 µsec rise	50 nsec to 1 msec	
1.1.3 Millisecond	0.1 msec rise	>1 msec	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 msec	0–4 p.u.
1.2.2 Medium frequency	5–500 kHz	20 µsec	0–8 p.u.
1.2.3 High frequency	0.5–5 MHz	5 µsec	0–4 p.u.
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5–30 cycles	0.1–0.9 p.u.
2.1.2 Swell		0.5-30 cycles	1.1–1.8 p.u.
2.2 Momentary			
2.2.1 Interruption		0.5 cycles to 3 sec	<0.1 p.u.
2.2.2 Sag		30 cycles to 3 sec	0.1–0.9 p.u.
2.2.3 Swell		30 cycles to 3 sec	1.1–1.4 p.u.
2.3 Temporary			
2.3.1 Interruption		3 sec to 1 minute	<0.1 p.u.
2.3.2 Sag		3 sec to 1 minute	0.1–0.9 p.u.
2.3.3 Swell		3 sec to 1 minute	1.1–1.2 p.u.
3.0 Long duration variations			
3.1 Interruption, sustained		>1 minute	0.0 p.u.
3.2 Undervoltages		>1 minute	0.8-0.9 p.u.
3.3 Overvoltages		>1 minute	1.1–1.2 p.u.
4.0 Voltage imbalance		Steady state	0.5-2%
5.0 Waveform distortion			
5.1 DC offset		Steady state	0–0.1%
5.2 Harmonics	0–100th	Steady state	0-20%
5.3 Interharmonics	0–6 kHz	Steady state	0-2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7%
7.0 Power frequency variations		<10 sec	

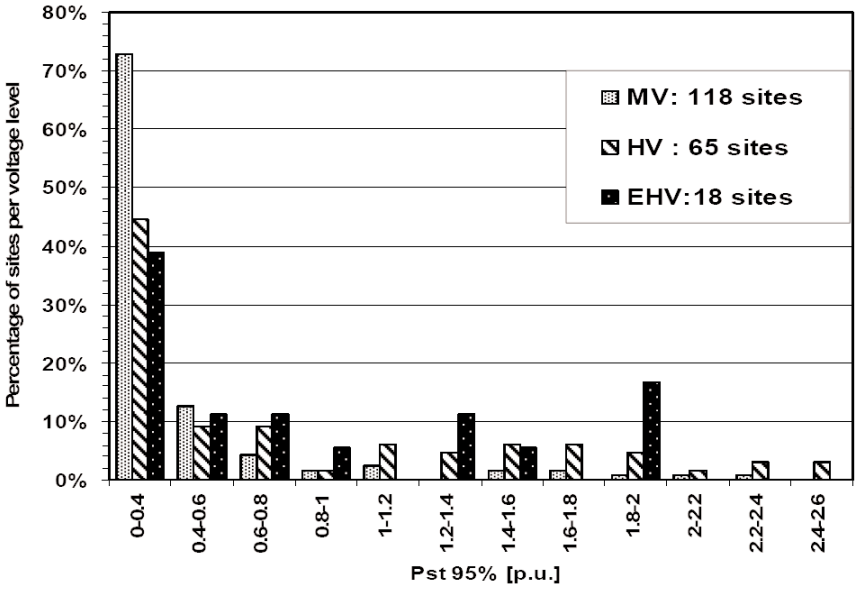
Source: IEEE Standard 1159-1995 (R2001)

Categorizing Voltage Fluctuations on an Amplitude (Magnitude) vs. Duration Plot



Source: UIE

Measurement Data for Flicker P_{st} 95 at MV, HV and EHV



The survey was comprised of sites at the medium voltage (MV), high voltage (HV), and extremely high voltage (EHV) levels. Most of the sites were characterized by low P_{st} 95% values (i.e., sites with a low level of fluctuating voltage), and most experienced flicker at the MV level. For more on Pst, please see *Flicker Meter Specifications* below.

Source: CIGRE C4.07/CIRED Working Group Report

In the figure on the left, these two areas are shown below "Overvoltages" and above "Voltage Dips (Sags)." Voltage fluctuations can last in duration from 0.5 cycles to very long duration events, including steady-state fluctuations (not shown in figure), greater than a few hours. For example, this graph indicates that a line voltage that fell to 5% of its nominal value is actually classified as a voltage fluctuation, not a voltage sag. The same is true for an electrical disturbance that resulted in an increase in line voltage up to 10%. If the disturbance is above 10% in amplitude, then it is classified as an overvoltage, not a voltage fluctuation.

Survey results for flicker are generally very limited. Most measurement campaigns evaluating flicker are performed when there is a specific problem resulting from a complaint of flickering lamps — usually incandescent, but in some cases fluorescent and high intensity discharge (HID) lamps. Problem sites attract the attention of customers and power quality engineers, especially when the lamp-ballast system is an amplifier of voltage fluctuations (i.e., has a gain factor greater than unity, see sidebar). The results are, therefore, not representative of the performance of the power system in general. (Most sites have very low flicker levels.) Results from a variety of surveys are provided in the figure on the bottom left; however, the report they come from cautions that these results should not be considered statistically valid due to small sample size.[3]

Understanding Gain Factor

A *gain factor* is a quantity used in power quality and system compatibility research to determine the degree to which a lighting device reacts to a voltage fluctuation. This factor can be used to determine whether a lighting device is an attenuator or amplifier of a fluctuating line voltage. The gain factor is given by the following equation :

$$GF = \frac{\%\Delta RI}{\%\Delta V} = \frac{(RI\text{max} - RI\text{min}) / RI\text{base}}{(V\text{max} - V\text{min}) / V\text{base}}$$

where

- *RI*max = maximum relative illumination (RI),
- *RI*min = minimum RI,
- *RI*base = average RI with no fluctuating line voltage,
- *V*max = maximum peak in the fluctuating line voltage,
- *V*min = minimum peak in the fluctuating line voltage, and
- *V*base = peak of fluctuating line voltage.

As an example of a gain factor calculation, the maximum relative illumination, *RI*max, was measured to be 2,192 lux as the lamp was flickering. The minimum relative illumination, *RI*min, was measured to be 1,886 lux as the lamp was flickering during the same test. The difference in the RMS value of the voltage, *V*max – *V*min was 0.05 Vac, and thus, the gain factor was calculated to be 3.2 lux/volt.

Gain factor can be calculated in a lighting laboratory by placing the luminaire under test in a photometric chamber and measuring relative changes in light level during voltage fluctuations. A photometer, corrected for human eye response, is used to measure the relative illumination output of the luminaire containing the lamp in question. By controlling the magnitude and the frequency of voltage fluctuations using a computer-controlled amplifier, the flicker response of the luminaire can be determined.

The gain factor of the incandescent lamp drops off at higher frequencies because of the thermal inertia of the filament. Because a 230-V lamp, typical in Europe, has a thinner filament than a 120-V lamp, used in North America, illumination changes can occur more quickly. Similarly, when voltage fluctuations are a sine wave rather than rectangular waveform, a different flicker response is observed. At 1 Hz, the rectangular-shaped voltage change causes about twice the level of flicker of a sine-wave fluctuation. As the frequency of modulation increases, thermal inertia of the lamp filament begins to mask these shape differences.

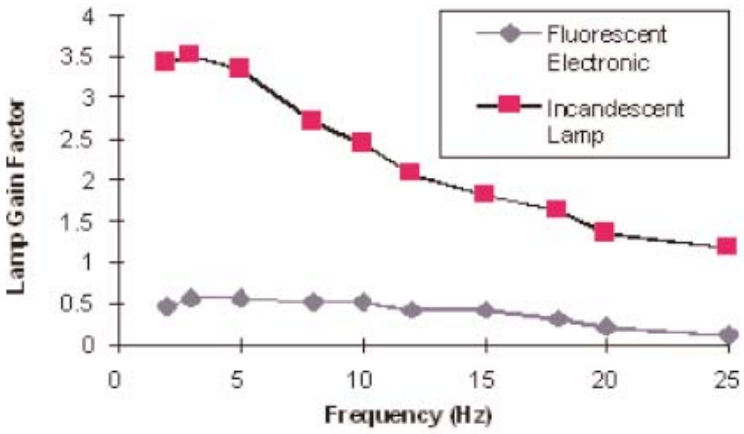
The Importance of Lamp and Other Equipment Types for Flicker

Predicting light change on the basis of voltage change carries some assumptions. For example, different types of lighting respond differently to voltage fluctuations. A standard lamp type must be declared to quantify flicker with a voltage measurement.

Historically, the standard lamp used for measuring flicker has been a 60-W incandescent lamp because of its ready availability and widespread use. These lamps have certain response characteristics that are unique among other types of lighting and even among wattage ratings within the same family. The incandescent lamp responds to step changes in RMS voltage but has a certain thermal time constant that does not allow the light output to change instantaneously. If the frequency of these step changes is increased, the lamp response is diminished. Eventually, the fluctuations can be repeated fast enough that the output from the lamp does not change. Consider the 50/60Hz AC voltage that supplies the lamp — it changes many times per second but produces no visible flicker. The effect on light output of the frequency of the power input is illustrated in the figure on the following page, which shows the 60-W lamp response versus the frequency of RMS step changes. Gain factor is the percentage of change in light output compared to the percentage of change in

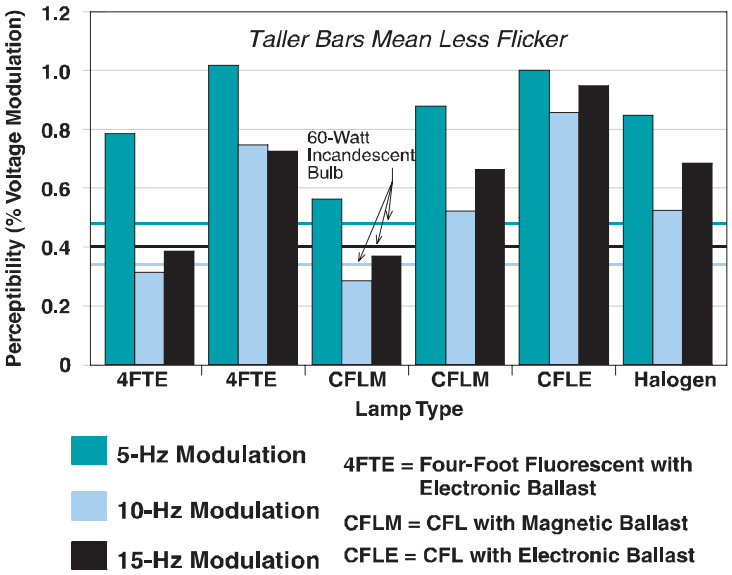
voltage input. The frequency scale refers to a square wave modulation of the 50/60Hz power frequency.

Incandescent Lamp Response to Square Wave Modulation of Frequency of Power (60 Hz)



A 60-W incandescent lamp operating at 120 V shows a change in lamp gain in comparison to a particularly well-behaved, practically flicker-free, electronic fluorescent lamp.

Flicker Perception Thresholds for Various Lamps at 5, 10, and 15 Hz



Flicker perception thresholds are compared for seven different lamp types based on the average of six observers per lamp. The lamps used were two 4-ft electronic fluorescent, 64 W and 80 W; two magnetic ballast compact fluorescent lamps (CFLs), 13 W and 15 W; one 15-W electronic CFL; one 45-W halogen; and a standard 60-W incandescent lamp.

Different lighting technologies have unique susceptibilities to voltage flicker (see figure on top left).[4] In addition, lighting technologies are different in how they respond to the flicker frequency of applied power. Although the incandescent lamp shown is more sensitive than fluorescent across all frequencies, this sensitivity is reduced greatly as the frequency of applied power is increased.

In contrast, fluorescent lamp arcs have very little thermal inertia and, therefore, respond quickly to voltage changes. Where the thermal time constant[5] for an incandescent at 120 V is about 28 milliseconds and for a 230-V lamp, about 19 milliseconds, a typical fluorescent lamp has a time constant of about 5 milliseconds. Consequently, fluorescent lamps are more sensitive to different voltage waveforms, harmonic-related phase shifts, and more rapid fluctuations.

Changes in lighting technology have been substantial, with ceiling, task, and special-purpose lighting now available in electronic-ballasted versions of fluorescent lighting. The level of flickering in these new lamps varies from slightly more to a lot less than the standard 60-W incandescent lamp. The figure on bottom left compares flicker perception thresholds for seven different lamp types.[6]

Using gain factor to predict the flicker performance of a variety of different lamp types has been effective in lab tests.

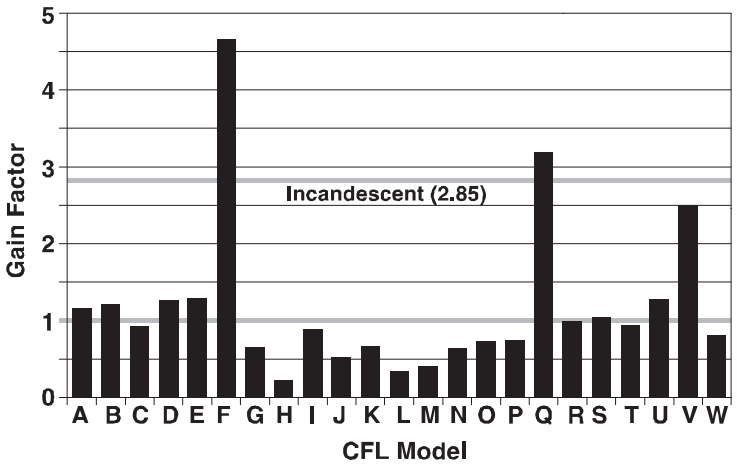
Research has been conducted to identify lighting designs with high gain factors (see sidebar on page 7) to provide utilities and their customers with some guidelines on selecting lighting devices for various applications. Conversely, lighting devices that are effectively insensitive to voltage fluctuations, for example, a lamp ballast that does not allow voltage fluctuations on the ballast input to result in fluctuations in the lamp current, may be used as a solution to localized flicker problems.

Using gain factor to predict the flicker performance of a variety of different lamp types has been effective in lab tests. More than 50 different lamps and lamp-ballast systems, including incandescent; both compact and 4-ft, magnetic and electronic fluorescent; and high intensity discharge types have been evaluated. The figure below shows the variation in gain factor at a voltage fluctuation frequency of 8 Hz for 23 different CFL models. Models F and Q are magnetic ballasts and the rest are electronic ballasts. Generally the electronically ballasted CFLs performed better than the magnetically ballasted CFLs. Below 25 Hz, most of the fluorescent lamps had significantly less flicker than an incandescent lamp. However, at higher fluctuation frequencies the fluorescent products had more flicker than the incandescent products. This becomes important in the case of interharmonic voltage distortions.

Incandescent Lamp Dimmers

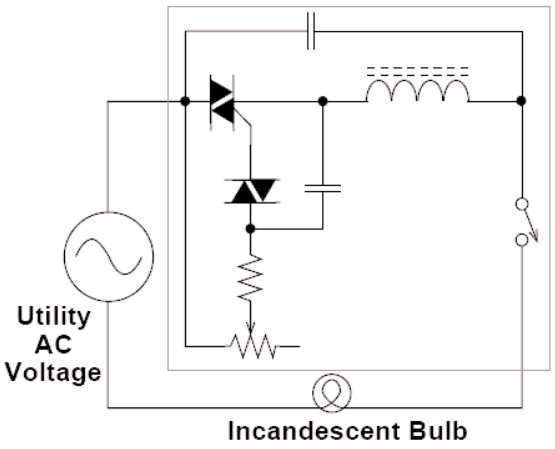
Lamp dimmers have also played a role in the number of flicker-related complaints. At one time theaters used a type of passive lamp dimmer called a rheostat — which was simply a variable resistor in series with an incandescent lamp or group of lamps — but those are now obsolete. Modern lamp dimmers use efficient active components to periodically block the voltage to an incandescent lamp and thus reduce the RMS voltage across the lamp, which in turn reduces the current through the lamp filament. Widely available in retail establishments, active dimmers are now commonplace in residential and commercial buildings. However, some electric utility customers have reported an increase of lamp flicker after installing active dimmers. The figure below shows a schematic of a typical active dimmer.

Gain Factors of Tested CFL Models at a Voltage Fluctuation Frequency of 8 Hz



Taller bars mean relatively higher flicker levels.

Schematic of a Typical Active Dimmer



EPRI conducted tests to determine the affects of dimmers on incandescent lamp flicker.

System compatibility testing was conducted by EPRI to determine how much an active dimmer affects the response of an incandescent lamp to flicker-causing voltage fluctuations. Three active dimmers were tested with a standard 60-W incandescent lamp. A rheostat-type dimmer was later tested to determine whether the voltage decrease across the lamp or the components of the active dimmers affected flicker.

The table below lists the four dimmers and their basic features. The rheostat-type dimmer was made of ceramic and Nichrome. Dimmer 2 was designed to be installed in place of a light switch; dimmer 3 was part of an incandescent bulb socket; and dimmer 4 was integrated into a "touch" lamp. The dimmer setting of the touch lamp was adjusted in discrete steps by simply touching the metal lamp stand. The other dimmers had continuous-range controls.

The 60-W lamp was installed in a light chamber. A photometer connected to a digital oscilloscope measured the light output of the lamp, and a computer program developed by EPRI controlled a function generator and linear amplifier to create voltage modulations during the flicker tests. A harmonics analyzer and digital oscilloscope monitored current distortion to record the waveform of the voltage across the lamp during various dimmer settings. To achieve a stable temperature of both the lamp and dimmer components, each dimmer and the lamp were operated together for 10 minutes before any measurements were taken.

For each test, the source voltage was modulated by a steady-state, square-wave voltage at an amplitude of 5% of nominal and at frequencies of 2, 3, 5, 8, 10, 12, 15, 18, 20, and 25 Hz. To determine a baseline flicker for the incandescent lamp, the flicker of the lamp without a dimmer was measured for each modulation frequency in terms of the lamp's gain factor. Then, each dimmer was connected to the lamp.

The following four dimmer settings were used during four different trials: 0%, 25%, 50%, and 75% dim (75% dim indicates the lowest light output of the four settings). However, dimmer 4, which did not have a continuous range, was tested only for its 0% and 75% dimmer settings.

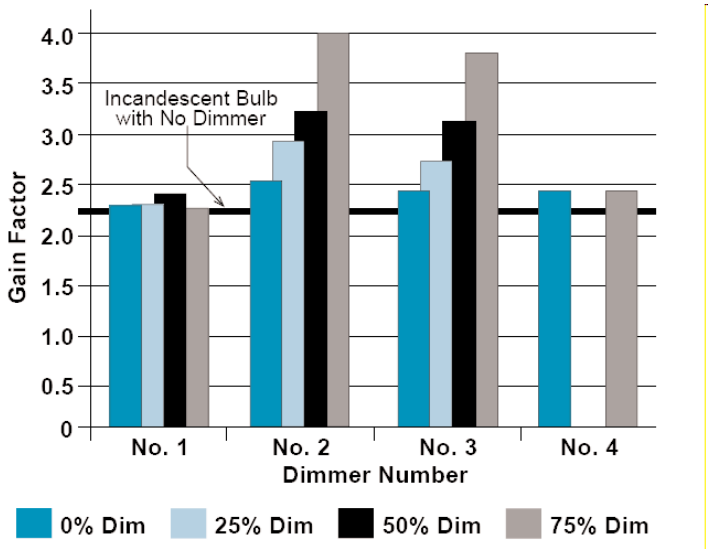
Basic Characteristics of the Four Dimmers Tested

Dimmer	Type	Range of dimming	Power (W)
1	Rheostatic	0 to 75%	1,000
2	Active/TRIAC[a]	0 to 100%	600
3	Active/TRIAC	0 to 100%	150
4	Active/TRIAC	Discrete[b]	150

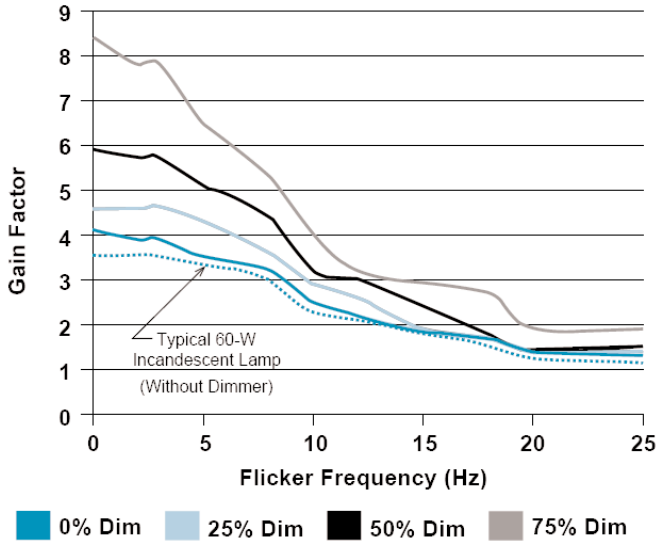
a. TRIAC = triode for alternating current.
b. Dimmer number 4 had three discrete dimmer settings: 0%, 75%, and greater than 90%.

The top figure below shows the results for a modulation voltage of 10 Hz, which is near the frequency of flicker most noticeable to the human eye.[7] For the active dimmers with a continuous range (0 to 100% dim), the gain factor increased as the dimmer setting increased. However, this increase in gain factor depended upon the frequency of the voltage modulation; the lower the modulation frequency, the greater the increase in gain factor (for example, see the frequency/gain factor response for dimmer 2 in the figure on the bottom right). The rheostat-type dimmer did not significantly increase the gain factor and at 0% dim, was in effect shorted out of the circuit. Dimmer 4 slightly increased the gain factor, but the increase did not depend upon the frequency of the voltage modulation.

Flicker Gain Factor for the Four Dimmers During a 10-Hz, 5% Steady-State Modulation of the Source Voltage



Gain Factor of Dimmer 2 for Modulation Frequencies from 0 to 25 Hz and Four Dimmer Settings



A Historical Perspective on Flicker

Lamp flicker caused by voltage fluctuations has been a topic of study for engineers and physiologists for more than 80 years. Among the types of engineers that have addressed flicker in this period are lamp, electrical power system, and compatibility engineers.

A number of historical milestone activities have taken place since 1891 regarding flicker-related topics, including the selection of the power-line frequency, the creation of the first flicker curve, and a number of flicker studies conducted by research organizations.

1891-The pioneers of the North American power industry select 60 Hz as the standard frequency for the electric power system to prevent visible flickering in open-type arc lamps. Europeans select 50 Hz based on the flicker response of enclosed-type arc lamps.

1921-A General Electric engineer researches human response to lower-frequency flicker (0 to 10 Hz) found in 115-V, tungsten filament lamps and caused by low-speed, motor-driven reciprocating compressors.

(continued on the next page)

A Historical Perspective on Flicker *(continued)*

1925-General Electric publishes the "GE Flicker Curve" rendered from the 1921 research. The curve eventually becomes a standard for voltage design in North American electric utilities.

1937-Utilities Coordinated Research completes a comprehensive study on human perception of flicker, which validates the GE Flicker Curve for cyclic flicker and recommends a voltage limit for noncyclic flicker.

1950s-Electric utilities become concerned about the "stroboscopic effects" of the new fluorescent lamps, but research confirms that the standard 120-V incandescent lamp remains the type of lighting most prone to flicker, especially at low pulsation rates.

1964-A modified GE Flicker Curve, for cyclic and noncyclic pulsations, is published in IEEE Standard 141, the IEEE Red Book.

1985-An IEEE survey reveals that 69% of the responding electric utilities used the updated GE Flicker Curve as their voltage standard.

1994-A flicker study conducted by EPRI and the Canadian Electrical Association finds that some new electronic and compact fluorescent lamps are more prone to flicker and some less prone than the standard incandescent. The study also reveals that some lamp dimmers tend to amplify light flicker.

Because flicker is entirely an issue of human perception, it is extremely difficult to quantify.

THE IMPACT OF FLICKER ON HUMANS

Since flicker doesn't interrupt, overheat, destroy, or affect the operation of customer loads or utility distribution equipment, it only becomes an issue if humans are annoyed.

Since flicker doesn't interrupt, overheat, destroy, or affect the operation of customer loads or utility distribution equipment, it only becomes an issue if humans are annoyed. The famous rhetorical question applies: "If a tree falls in the forest and there is no one there to hear it, does it make a sound?" Similarly, if voltage fluctuations are occurring on a circuit, but there is no lighting on that circuit or, if lighting does exist, there are no human observers, does a flicker problem exist? In this case, the answer is "no."

Because flicker is entirely an issue of human perception, it is extremely difficult to quantify. Human observers vary widely in their responses to flickering lights and are often able to get used to it after a while. Even the presence of sunlight is a mitigating factor. In the case of a small-town plant, often many local residents understand the source of the fluctuating lights, live with it for their entire lives, and become conditioned to the stimulus. In another example, a wind turbine owner was pleased to see the lights flicker, because to him, voltage fluctuations meant that his turbines were spinning and that he was generating electricity.

Early Flicker Experiments

Early human perception experiments, like the one shown in the figure on the following page, have been conducted to determine how perceptible people are to flickering lamps under various conditions. At the time early experiments were conducted, only standard incandescent and fluorescent lamps were available.

Early Human Perception Experiment for Lamp Flicker



The table below represents the light sources that were used in an early flicker human perception experiment. A 100-W incandescent lamp was used for the first and third experiments, with the first being powered from an AC source and the third being powered from a DC source. In the second experiment, a 15-W fluorescent lamp was also powered from an AC source. During the experiment, the line voltage to the lamps was varied from ½ to 10 cycles, depending upon the type of lamp, and the flicker frequencies used were 0.1, 15, and 30 Hz. The number of observers was 8, 13, and 300 with the number of observations varying from 200 to over 12,000. The results indicated that the observers in all cases perceived the flicker intentionally (i.e., when the flicker was pointed out to them), and noticed the flicker from the 100-W incandescent lamp powered by the AC line voltage casually, or without prompting.

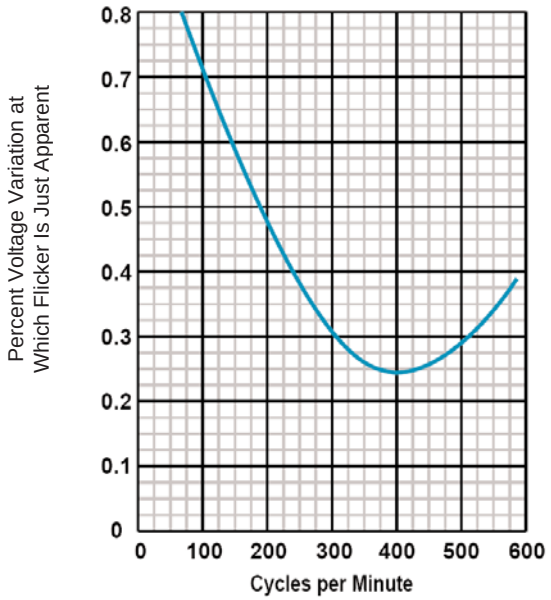
Range of Tests Used in an Early Human Perception Flicker Experiment

	Experiment 1	Experiment 2	Experiment 3
Lamp type	100-W incandescent	15-W fluorescent	100-W incandescent with DC
Duration of dip (cycles, t_{DIP})	½, 1, 2, 5, 10	1, 5	2, 5
Flicker frequency			
Minimum	.1	.1	.1
Maximum	30	30	15
Number of observers	300	8	13
Number of observations	12,000+	200	400
Intentional observations	yes	yes	yes
Casual observations	yes	no	no

Determining Perceptibility and Irritability

Lighting systems that flicker are the most perceivable consequence of voltage disturbances to residential and commercial customers. Yet today's North American flicker standards can be traced to a flicker curve composed in 1921 by Willard C. Brown, an engineer from the National Lamp Works of General Electric. This curve was not published until 1925. The curve, shown in the figure below, conveys the relationship between the magnitude and frequency of voltage fluctuations and human perception of the flicker in an incandescent lamp resulting from these voltage fluctuations.

Original General Electric Flicker Curve



Subsequent flicker research has not kept up with the remarkable advances in lighting technologies, such as the development of electronic fluorescent, HID lamp-ballast, and LED lighting systems. Although the GE Flicker Curve has served the utility industry well and is still valid for standard incandescent lighting, the introduction and widespread use of high-tech magnetic and electronic ballasts raise questions about its applicability to modern lighting.

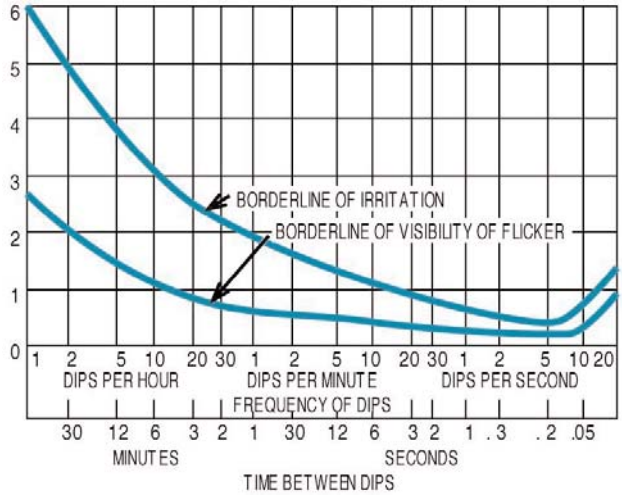
The human eye and brain also have certain filtering characteristics when subjected to varying luminous intensities. Consider, for example, the principle of motion pictures, where rapidly appearing still frames give the illusion of movement. All of these factors play a role in the prediction of human reaction to changes in light caused by a voltage fluctuation.

A well-known early attempt to quantify flicker was developed by General Electric in the 1920s. The research included human observers who were invited to read while being subjected to controlled fluctuations in light. By varying the frequency and magnitude of dips, the researchers developed a curve representing the borderline where most people began to perceive light flicker and another curve representing the borderline of irritation.

The curve was later modified and published by IEEE in Standard 141 (see figure on the following page).[8] The curve shows highest sensitivity to flicker at about 7–8 dips per second. Highest sensitivity occurs where the lowest percent voltage dip causes the undesirable human response.

The IEEE curve was developed using step changes in RMS voltage. The model is better applied to motor starting (the environment in which it was born); fluctuations caused by other sources, like arc furnaces, are random in nature and have irregular wave shapes, making a prediction of the flicker response very difficult. This curve is still used by many electric utilities today as a tool for imposing flicker limits on industrial customers connected to the grid.

Flicker Thresholds for Incandescent Lamps

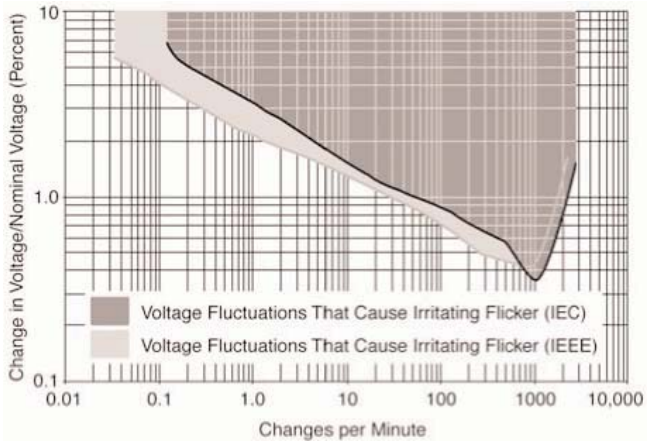


The IEEE has published a rule-of-thumb guideline for incandescent lamps correlating the frequency and RMS amplitude of voltage dips with impact on nearby persons. Although one might suppose that any light flicker would be annoying, the reality is that light flicker to the eye is much like noise to the ear — a little is noticeable, and a lot is distracting. In general, as the frequency of dips goes up, the lower the amplitude of the voltage fluctuation necessary to produce annoyance. At about 7–8 dips per second, however, visibility and irritation improve precipitously.

MEASURING FLICKER

As useful as the IEEE curve is, however, it does not tell us how to actually measure the voltage fluctuations. In North America, IEEE published two recommended practice documents, and two different flicker meters have been designed. Both designs indicate flicker levels by separating the voltage fluctuations into magnitudes and frequencies. The results are then plotted against the flicker curve.

Comparison of IEC and IEEE Flicker Irritation Thresholds



Although derived from independent research, the IEC and IEEE flicker irritation thresholds are remarkably similar.

The IEC Flicker Measurement Method

In 1992, the International Union of ElectroHeat (UIE) in Europe combined existing flicker standards from France, England, Germany, and Japan into one new measurement method. This method was later adopted by the International Electrotechnical Commission (IEC) and became known as IEC 868. It is now called IEC 61000-4-15. This flicker measurement method is built on years of combined research by engineers and scientists in the areas of the human ocular system, brain reaction, and lamp response. In 1999, IEEE voted to accept the European IEC methodology of flicker measurement.

One outcome of the comprehensive research was a new irritation curve. This curve is shown in comparison to the IEEE 141 curve in the figure on the left.[9] Despite the fact that the two curves were derived from independent research, they are strikingly similar. Note that in the comparison, the x-axis is scaled in changes per minute. For this curve, a single voltage fluctuation is assumed to cause two lighting level (or flicker) changes per minute — once when the voltage first changes and again when voltage returns to normal. The IEC curve shows greater human sensitivity than the IEEE curve at around 1,000 changes per minute, or 8.3-Hz modulation, but less sensitivity for all frequencies lower than about 700 changes per minute or 5.8-Hz modulation.

Measuring flicker has long been a challenge.

Flicker Meter Specifications

Given the phenomenon's intermittent nature, measuring flicker has long been a challenge. The degree of voltage variation is not only somewhat tricky to gauge, a flicker meter must also transform voltage fluctuations into an approximation of the physiological sensation that an average observer would experience when viewing a flickering lamp. This requires a model of the lamp-eye-brain chain that will accept as input the amplitude of the voltage fluctuations and return an output level corresponding to the intensity of the perceived sensation (see figure below).

The output of the IEC flicker meter are two simple indices:

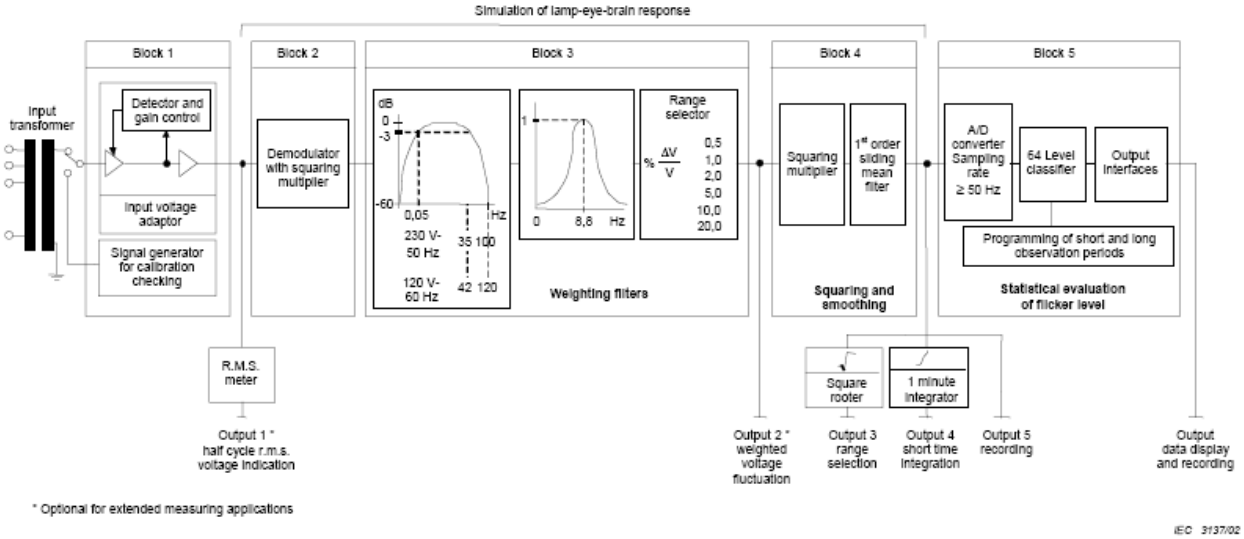
- P_{st} (where st stands for "short term")
- P_{lt} (where lt stands for "long term")

P_{st} is a measure of the severity of light flicker based on measurements taken over a 10-minute interval and is a statistical amalgam of an array of specific flicker levels observed during the interval. A new value of P_{st} is generated every 10 minutes during the monitoring period. The 10-minute period was selected as a compromise. It is long enough to prevent overemphasis of isolated voltage changes, such as voltage sags, but is also short enough to characterize in some detail the flicker from disturbing equipment or factory processes having a long duty cycle.

Despite the involved nature of how P_{st} is calculated, the result is very practical. A P_{st} value of 1.0 or greater indicates circumstances where at least 50% of the population can be expected to complain of light flicker. The index P_{lt} is generated every 2 hours and is based on sort of vector sum of successive measurements of P_{st}. The 2-hour period was chosen because it is long enough to cover most of the duty cycles of industrial processes and also long enough to cope with the intermittent operation of loads that simultaneously or randomly cause flicker.

Again, the outcome of the P_{lt} calculation is very practical. If P_{lt} is 0.8 or greater, complaints are likely.

Lamp-Eye-Brain Response Model from IEC 61000-4-15



As is clear in the processing chain shown, measuring flicker is not a trivial matter. The input is a simple voltage measurement and (after subsequent processing, smoothing, and fluctuation calculations) the output are the two principal short- and long-term flicker metrics of P_{st} and P_{lt}.

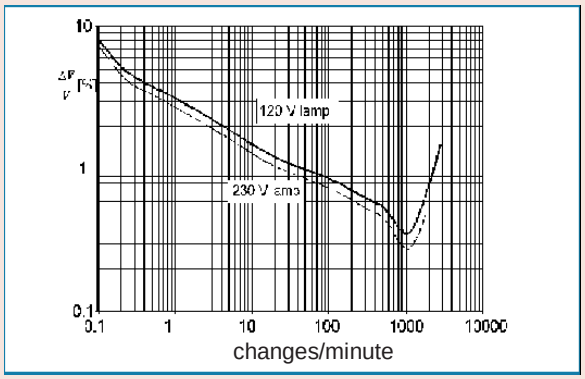
As with many other power quality measurement metrics, there are ways that the P_{st} and P_{lt} metrics can be modified at the time of measurement. For example, flicker meters can include means for filtering out unusual or extraneous events. This is usually done by filtering out the most unlikely (1% or 5% for example) incidents of flicker, thereby concentrating on only the flicker levels that occur 99% or 95% of the time, respectively denoted as $P_{st99\%}$ or $P_{st95\%}$.

A Historical Perspective on Flicker

The IEC flicker meter was developed in Europe, where 230-V lamps are used. Lamps in North America, which operate at 120-V supply voltage, conduct a higher current at the same wattage and are, therefore, constructed with thicker filaments. Since thicker filaments have a higher thermal inertia, the 120-V lamps are less sensitive to voltage fluctuations than 230-V lamps of the same wattage. The figure shows the difference in response between a 120-V and a 230-V lamp, both being 60 W.[10]

For this reason, the original IEC flicker meter was not directly applicable to measurement of flicker in North America. Over the past few years, however, the IEC flicker measurement standard has been adapted to include the characteristics of 120-V lamps for measurement in North America, based on the lamp characterization tests performed at the Power Electronics Applications Center laboratory operated by EPRI in Knoxville, Tennessee, USA.

Comparison of Flicker Response of 60-W Lamps Operating at 120 V and 230 V



Because of construction and different thermal constants, 60-W lamps designed for 120 V (common in the U.S.) will generally experience lower levels of flicker than lamps designed for 230 V (common in Europe). As such, different flicker calculations are required for each.

Source: IEC 61000-4-15

Using a Flicker Meter

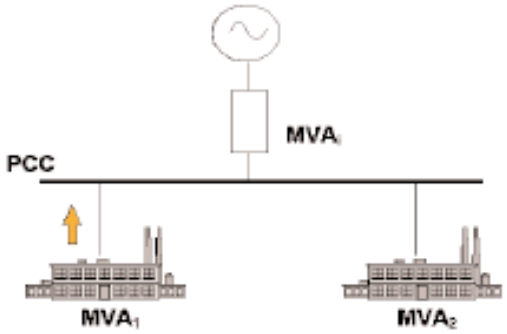
Most flicker meters can accept an input signal of 100 V to 600 V without additional hardware; however, it would not be a bad idea to have potential transformers available at the site. Most loads that produce flicker are connected to three phases. Although the flicker should be nearly the same on all phases, it is better to measure each of them if the metering capability exists. Measurements should be made line-to-neutral, the way lighting loads are connected.

Measurement of flicker is usually done only with voltage. A current measurement could be a helpful tool for diagnosis to help correlate the P_{st} with any peaks in current and to determine the source of flicker when more than one flicker-producing load is in use. However, current measurement is not necessary when making a simple flicker measurement.

Meter Connection

Voltage fluctuations should be measured at the PCC between the disturbing load and the flickering lighting load. The figure below illustrates a possible scenario. In this case, a metering point at load MVA_1 is nearest to the point of common coupling and provides the worst-case fluctuations that may be seen by a neighboring customer, shown as MVA_2. Attaching a flicker meter higher up in the distribution system at the PCC — say nearer the utility substation (MVA_i) — provides a measure of what is seen by other feeders on that substation as well as what is likely to be seen by other end-user facilities in the area.

Flicker Point of Common Coupling (PCC)



The point of common coupling (PCC) is the point on the electric delivery system nearest a flicker source (MVA_1) at which another load (MVA_2) could be connected and, presumably, adversely affected. The PCC is most commonly a distribution feeder or a utility substation

Measurement Period

Because it is a periodic phenomenon, there is no "instantaneous" measure of flicker. Rather, flicker must be evaluated over a period of time. An instantaneous flicker level, even if it were possible, could not give the whole picture, because most flicker-producing loads are cyclical or random in nature.

There are two complementary strategies when measuring flicker. The first, as described above, focuses on measuring maximum levels of P_{st} for one or more 10-minuteintervals. The second is a statistical analysis that should be performed to determine the percentage of time that a set of predetermined flicker levels have been exceeded over a certain measurement period. For example, in Japan the primary flicker metric is ΔV_{10max}, which is a measure of the maximum level of RMS voltage fluctuation that occurs 10% of the time or more. While the P_{st} method is more rigorous, the Japanese method is simpler to implement.

Modern flicker meters, however, have plenty of computational horsepower to do complex algorithms, even in inexpensive devices. These flicker meters have built-in statistical analyses to produce results using the two standard 10-minute and 2-hour flicker measurement periods. Although a new value of P_{st} can be derived from every 10 minutes of measurement, a single 10-minute measurement is usually not considered sufficient to assess the flicker levels at a particular site. Measurements should be taken for at least one cycle or shift of the manufacturing process under investigation, and a measurement period of several days or weeks is recommended for added statistical rigor.

LIMITING AND PREVENTING FLICKER

So what level of voltage flicker is acceptable for what setting? The guidelines and standards described below offer some guidance. However, at the end of the day, the final determination will likely be made by the eyes of those persons working under the affected incandescent lights.

Compatibility and Planning Levels

UIE flicker meter measurements taken at the PCC can be used to determine compatibility levels of a customer with the power network.

IEC standards have been very influential in the area of voltage flicker.

The P_{st} values can be used to predict compatibility, with given data on the power system and the load. For example, the following formula gives the expected P_{st} for an arc furnace at the PCC using a furnace emission coefficient that may be provided by the vendor:

$$P_{st99\%} = K_{st} (S_{ccf}/S_{ccn})$$

where K_{st} is the arc furnace emission coefficient for P_{st}, S_{ccf} is the arc furnace short circuit level at PCC, and S_{ccn} is the network fault level at the PCC.

The table below suggests compatibility levels as indicated by UIE for low-voltage situations. At low voltages, lamps may be connected and, therefore, complaints may occur. Planning levels are provided for a PPC at medium-and high-voltage levels where there is no possibility of annoyance because lamps are not directly connected at these levels.

IEC Standards

IEC standards have been very influential in the area of voltage flicker. In fact, IEEE Standard 1453-2004, *Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems*, is largely an adaptation of the IEC 61000-4-15 standard. Presented below are some useful highlights of IEC standards on flicker. IEC Standard 61000-4-15 is not designed to limit values of flicker severity but to provide basic information for the design and instrumentation of an analog or digital flicker meter according to UIE-IEC specifications.

Limits and Evaluation for Low-Voltage Equipment (<16 A)

IEC Standard 61000-3-3 gives limits and evaluation procedures for low-voltage equipment with current ratings less than 16 A. When determining compliance with the limits, there are different ways of evaluating P_{st}, as shown in the table on the following page. Any voltage fluctuation can be assessed using the flicker meter measurement procedure. Direct measurement is most appropriate for loads already connected to a supply.

Care should be taken in any evaluation, other than direct measurement (under actual operating conditions), to match the duty cycle of the equipment. IEC 1000-3-3 specifies limits of $P_{st} = 1$ and $P_{lt} = 0.65$ for low-voltage equipment with a current rating less than or equal to 16 A. Furthermore, performance of this equipment should meet three voltage variation requirements:

- It should not produce a maximum relative RMS voltage fluctuation of more than 4%
- It should not produce a steady-state voltage change of more than 3%
- The period during which relative voltage change exceeds the threshold level [d(t)] shall not exceed 3 % for more than 200ms.

UIE Compatibility and Planning Levels

Measurement	Low-Voltage Compatibility	Medium-Voltage Planning	High-Voltage Planning
P_{st}	1.00	1.00	0.79
P_{lt}	0.74	0.74	0.58

Methods of Evaluating P_{st}

Types of Voltage Fluctuations	Methods of Evaluating P_{st}
All fluctuations	Direct measurement
Voltage fluctuations with known U(t)	Simulation, direct measurement
Voltage fluctuation waveforms corresponding to existing shape-factor curves	Analytical method; simulation; direct measurement
Rectangular voltage changes at known frequency	Use P_{st} = 1 flicker curve

The standard also stipulates: "If the voltage variations are due to manual operations or if their frequency is less than one per hour, the P_{st} and P_{lt} values requirements do not apply. The three requirements for the voltage variations must be applied in cases with previously indicated values multiplied by a factor of 1.33. The limitations are not applicable to emergency work or stoppages."[11]

IEC Limits and Evaluation for Low-Voltage Equipment

IEC Standard 61000-3-5 gives limits and evaluation procedures for low-voltage equipment with current ratings greater than 16 A that are intended to be connected to a low-voltage public supply distribution network. The limits are the same as those given in IEC Standard 61000-3-3. It is recognized, however, that a lower supply impedance will be needed to meet these requirements for larger equipment. In addition, IEC 61000-3-5 recognizes equipment that may produce voltage fluctuations at a rate of less than one per hour. In these cases, the limits of P_{st} and P_{lt} are not applicable. The maximum RMS voltage deviation is limited to 1.33 times the 4% limit of IEC 61000-3-3. IEC 61000-3-5 specially recognizes that low-voltage equipment with a current rating greater than 75 A should be evaluated based on the actual supply impedance at the connection point. P_{st} can then be estimated based on the relative size of the load volt-amperage and the supply transformer volt-amperage rating. The P_{lt} limit is set equal to 0.65 P_{st} for equipment with current ratings >75 A.

The limits given in the standard are:

- P_{st}: 1.0 or less
- P_{lt}: 0.65 or less

It should be noted that IEC 61000-3-3 and 61000-3-5 are considered to be "equipment standards" by which manufacturers of low-voltage equipment can design their products. However, the limits and evaluation procedures apply equally well to both the design phase and the operational phase of low-voltage equipment. The limits set forth serve to limit fluctuations below thresholds of irritability for users connected to the same supply circuit, regardless of whether or not equipment was designed according to these standards. For this reason, the limits of 1000-3-3 and 1000-3-5 can be applied in North America where limits are presently not placed on equipment manufacturers. For uses other than equipment design, however, existing levels of background fluctuations should be taken into account.

IEC 61000-3-7 gives suggested limits and evaluation procedures for equipment connected to medium- and high-voltage supply systems.

Flicker Guidelines for Medium and High Voltage (IEC 61000-3-7)

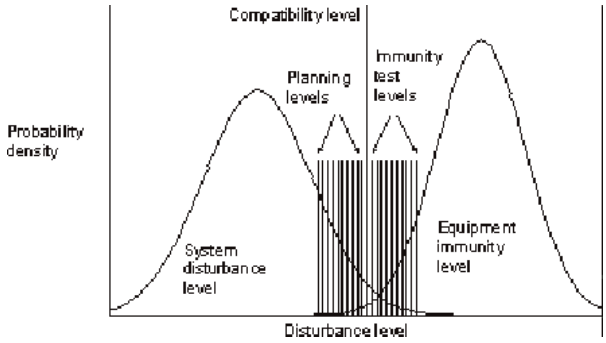
The IEC is currently undertaking a revision of a technical report first issued in 1996 and intended to guide engineering connections of large flicker-producing loads to public power systems. This document is a guideline, not a requirement. As such, IEC 61000-3-7 provides information to help electric power distributors set their own internal guidelines and practices for connection of large fluctuating loads.

IEC 61000-3-7 gives suggested limits and evaluation procedures for equipment connected to medium- and high-voltage supply systems. Note that the IEC defines medium voltage as 1 kV < MV = 35 kV and high voltage as 35 kV < HV = 230 kV. Extra-high voltage is considered to be >230 kV. Specific limits are not given that must be followed. The document recognizes that the limit values for P_{st} and P_{lt} will vary between utilities, depending on the specifics of both the loads served and the supply network. Indicative planning levels, which are the quality targets of a supplying utility, are given in the table below.

These levels are evaluated on a statistical basis. As a general guideline, P_{st} and P_{lt} should not exceed the planning levels more than 1% of the time (that is, a 99% level of confidence), with a minimum assessment period of 1 week. IEC 1000-3-7 distinguishes between P_{st} and P_{lt} values measured throughout a supply system and those associated with a particular fluctuating load. Planning levels (usually denoted as L_{Pst} and L_{Plt}) apply throughout a supply system; the aggregate effects of all fluctuating loads must be taken into account.

IEC 61000-3-7 also provides emission limits for individual loads (denoted as E_{Pst} and E_{Plt}) that should be met so that the combined effects do not exceed planning levels. These guidelines are intended to minimize the likelihood that there will be significant and frequent overlap between the level of voltage fluctuation on the supply system and levels of flicker vulnerability in end-use equipment, as illustrated below.

Achieving System and Load Compatibility



Managing flicker is a process of insuring that the levels of voltage fluctuation on the power delivery system do not significantly or frequently overlap with the range of equipment sensitivities in end-use loads. Although some overlap is inevitable, given the diversity of loads and the vagaries of real-world electrical systems, guidelines like IEC 61000-3-7 can help to minimize exposure.

Planning Levels for Medium-, High-, and Extra-High-Voltage Systems

	Indicative Values of Planning Levels	
	Medium Voltage	High to Extra-High Voltage
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

The IEC 61000-3-7 technical report proposes guidelines for evaluating the acceptability of the connection of large fluctuating loads to MV and HV public power systems. Technical report IEC 61000-3-7 states that the consumer is responsible for maintaining his emissions at the PCC below the limits specified by the utility. On the other hand, the utility is responsible for the overall control of disturbance levels under normal operating conditions. It also mentions that the utility and the consumer should cooperate when necessary to identify the optimum method to reduce emissions. The design and choice of method for such reduction are the responsibility of the consumer.

MITIGATION

In some cases, solving a flicker complaint may be as easy as changing a lamp or a lighting fixture. EPRI has used gain factor to predict the flicker performance of a variety of lamp types, including incandescent; compact and 4-foot, magnetic and electronic fluorescent; and high intensity discharge. Incandescent lights are especially susceptible to flicker, and dimmer switches can almost double the change in light output for a typical voltage change compared to the same lamp with no dimmer. Modern lighting shows promise for resisting flicker, although for fluorescent lights, much depends on the model and ballast type. The test results are being used to influence lamp manufacturers to design more flicker-free products. Unfortunately, if relamping doesn't work, flicker problems can be profoundly expensive to solve.

In some cases, solving a flicker complaint may be as easy as changing a lamp or a lighting fixture.

Utility Solutions

On the utility side, possible solutions can be expensive, and they usually focus on either increasing the stiffness of the electrical supply (so that voltage fluctuations are lessened) or adding new technologies, such as dynamic VAR compensation, to intelligently smooth and stabilize voltage levels. Further options include upgrading a substation transformer or building a new dedicated substation for a disturbing load. These options are expensive and rarely chosen. Instead, utilities are sometimes successful in isolating a plant from as many customers as possible by opening tie points in the distribution circuit. Or they might try working with a plant to investigate how its load is affecting the system and what changes can be made on that end.

When dealing with voltage fluctuations on the supply side, there are, in general, two approaches that can help to reduce the amplitude of voltage fluctuations:

- **Increase the short-circuit power level of the network:** By increasing the capacity (usually measured in MVA) of the electrical system serving a flicker-prone feeder, one can reduce the percentage level of voltage fluctuation. The current pulses that are causing the problem aren't lessened, but their impact on voltage levels is reduced. While this approach sounds straightforward, it also tends to be exceedingly expensive.
- **Decrease the reactive power flow from the network:** Reactive power levels are fundamental to voltage stability. Increasing the amount of reactive power available on the distribution network can reduce the flow of reactive power, thereby improving voltage fluctuations. The most common approach to this mitigation method is the progressive addition of capacitor banks. In some extreme cases, dedicated, sophisticated electronic static- or dynamic-VAR compensation systems can be installed in proximity to flicker-causing loads. Again, however, the cost of these solutions can be very high.

Static VAR compensators provide one option for addressing flicker problems.

Industrial Customer Solutions

On the customer side, static VAR compensators provide one option for addressing flicker problems. These silicon-controlled rectifier devices are installed near the plant causing the disturbance, and they attempt to provide reactive power as needed, which effectively reduces RMS variations on the power system. Other solutions involve reconfiguring equipment.

Case Study: Flicker Mitigation for Metals Fabrication

Complaints of flickering lamps came flooding into the offices of a local electrical utility when a manufacturer of condenser tubes for residential refrigerators installed a three-phase, 1,500-kVA resistive spot welder to fasten the condensers to steel wire used for heat dissipation and structural support. To fill a backlog of condenser orders from a major refrigerator manufacturer, the condenser manufacturer was running the welder at full capacity, 24 hours a day. The complaints drove the utility and user to work together to quickly determine ways to fix the problem and keep the welder running.

Investigators began taking measurements with a UIE/IEC flicker meter configured for 120-V lamps and recording the power system configuration, while factory personnel experimented with welder setup. The flicker meter, shown in the figure at top right, used during the investigation included an interface module, a laptop computer, and cables — all of which fit in a briefcase. When the Pst output from the flicker meter was above 1.0, utility customers connected to the same feeder would likely notice flicker in incandescent lamps. The threshold is higher for fluorescent lighting, so flicker of fluorescent lamps inside the facility indicated serious voltage fluctuations were going on.

Applying a Flicker Meter

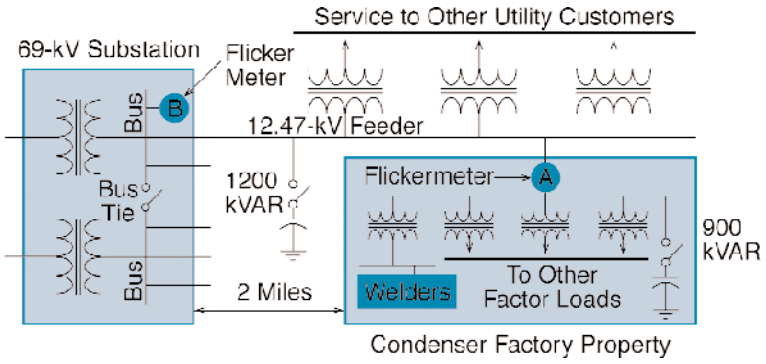


Flicker meters are an essential and sophisticated tool for diagnosing of voltage fluctuations.

As shown in the single-line diagram on the following page, a flicker meter was placed at the factory service entrance (a few hundred electrical feet from the welder transformer; point A in figure). Voltage fluctuations were measured at 2 to 2.4 P_{st}. The plant power consumption, voltage distortion, and current distortion were also monitored and recorded at regular intervals using a three-phase power monitor. On the same day, the flicker meter was moved to the utility 69-kV substation about two miles away and installed at a 12.47-kV oil circuit breaker on the feeder serving the condenser factory (point B in the figure).

Investigators tried different electrical and mechanical configurations for the new welder to see what effect they had on the power system voltage. To see if the older welder contributed to the voltage fluctuations, they also recorded its operating schedule and compared it to the flicker meter records. All this information was used to make electrical system and welder changes that would mitigate the fluctuations.

Single-Line Diagram Showing the Utility System, Factory Service, and Monitoring Points



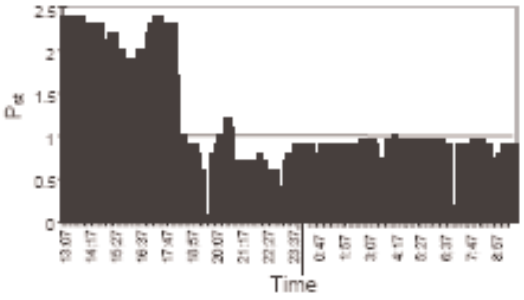
Measurement of flicker at multiple system points is a common approach for identifying fluctuation-causing loads and for assessing the impact of flicker.

Power system tests included varying the 1200-kVAR compensator at the substation (on or off), the 900-kVAR compensator at the facility (on or off), and the bus tie at the substation (open or closed). Changes in reactive compensation and the bus tie did not significantly affect the voltage fluctuations at the substation or service entrance. Closing the bus tie shown below slightly lowered the P_{st} at the factory service entrance from 2.4 to 2.0, but it also led to more flicker complaints from newly affected customers now tied to the distribution feeder that served the welder.

During the testing, the welder kept operating at a high throughput, with hope that production levels could be maintained without producing flicker. Suspecting that simultaneous firing of electrode pairs was the main cause of the light flicker, investigators changed the firing sequence from two at a time to one at a time and decreased the weld time from two to one cycle per weld. When the welder was reconfigured to fire electrode pairs individually for a duration of one cycle, the recorded Pst at the service entrance dropped below the level expected to cause light flicker, from >2.0 to an acceptable level of 0.8, as seen in the figure on the right.

Next, the cam speed and weld heat were varied to determine the maximum throughput of high-quality welds. After each change in welder configuration, investigators tested the weld strength of random condenser samples by pulling on structural wires using a weld test jig. In this way, the investigators determined that a maximum cam speed of 107 rpm and a weld heat of 83% achieved the greatest throughput of high-quality welds.

Recorded Flicker Meter Output at Service Entrance



Reconfiguration of how a welder operated reduced P_{st} measurements to acceptable levels. Fortunately, this was a low-cost and easily implemented solution.

Changing the firing sequence of the electrode pairs from two at a time to one at a time and changing the cam speed from 60 rpm to 107 rpm was determined to be the most cost-effective option for reducing flicker and maintaining a high production level. The condenser manufacturer was able to reduce voltage fluctuations at the substation bus to a level that did not create observable flicker. Reconfiguring the welder also decreased the energy consumption per weld. After the welder was reconfigured, complaints about flicker in the area ceased. Except for the cost of the investigation, reconfiguring the welder didn't cost anything and enabled the condenser factory to maintain a high production level and meet the backlog of orders for refrigerator condensers.

NOTES

1. Deflandre and G. Desquilbet, "Monitoring of Power Quality," in Proceedings of the EPRI Power Quality Applications Conference, 1994.
2. Adapted from International Union for Electricity Applications (UIE), *Guide to Quality of Electrical Supply for Industrial Installations—Part V: Flicker* (1999).
3. International Council on Large Electric Systems (CIGRE) C4.07 and International Conference on Electricity Distribution (CIRED) Working Group Report
4. R. Bergeron et al., "Voltage and Lamp Flicker: Basic Concepts, Recent Advances, and Case Studies" (October 1997).
5. A system's time constant is generally defined as the time required for a system's output to reach approximately 63% of its final value in response to a step change in input. A shorter time constant is generally indicative of a more responsive or sensitive system.
6. EPRI Power Quality Testing Network (PQTN) Briefs: *Perception Thresholds of Flicker in Modern Lighting* (no. 24, September 1995), *The Effect of Lamp Dimmers on Light Flicker* (no. 25, September 1995), *Lamp Flicker Predicted by Gain-Factor Measurements* (no. 36, July 96), *Lamp Flicker in Compact and Four-Foot Fluorescent Lighting* (no. 37, August 1996) (Knoxville, TN: EPRI Power Electronics Applications Center).
7. EPRI [6].
8. IEEE Standard 141: *Recommended Practice for Electric Power Distribution for Industrial Plants* (Piscataway, NJ: The Institute of Electrical and Electronics Engineers Color Books, December 1993).
9. IEC 61000-4-15: *Electromagnetic Compatibility (EMC) —Part 4: Testing and Measurement Techniques. Section 15: Flickermeter — Functional and Design Specifications* (February 2003).
10. Adapted from IEC [9], Table 1.
11. IEC 1000-3-3: *Voltage Fluctuations and Flicker*.