1C.5.1—Voltage Fluctuation and Flicker

1. Scope

This document contains guidelines regarding maximum acceptable levels of voltage fluctuation and light flicker in the power system. This document also discusses the causes of voltage fluctuation and light flicker, and gives advice on minimizing this problem. This document does not deal with voltage transients and other short-term disturbances from normal system operations; these are discussed in Engineering Handbook document 1C.6.1.

2. References and Resource Documents

This handbook reflects the requirements of the industry documents listed below that were in effect at the time of publication. When a referenced document is superseded by an approved revision, the revision shall apply.

IEEE 1453, *Recommended Practice — Adoption of IEC 61000-4-15:2012, Electromagnetic compatibility (EMC) — Testing and measurement techniques — Flicker meter — Functional and design specifications*

IEC 61000-4-15, *Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications*

3. Application of Guidelines

These guidelines should be used during the planning and design of new additions to the power system, including new loads. These guidelines should also be used to evaluate the impact of existing loads. Fluctuations greater than the limits in these guidelines may be allowed if the local customers are tolerant. All new installations should be designed to meet these limits if other customers are exposed. For flicker problems with existing loads, and in the absence of objective flicker meter measurements, customer intolerance to voltage fluctuations is indicated by the first complaint, at which point the problem should be investigated.

4. Definitions

The following expressions are defined as used in this standard.

Flicker meter. A device used to measure voltage fluctuations and objectively infer light flicker therefrom. The inferring methodology is defined in both IEC 61000-4-15 and the IEEE 1453 standard for North America.

Extra high voltage (EHV). Voltage greater than 230 kV.

High voltage (HV). Voltage greater than 35 kV but less than or equal to 230 kV.

HVAC. Heating, ventilation, and air conditioning equipment. This includes heat pumps.

Light flicker. Variable light production from a light source, sometimes due to voltage fluctuation.

Low voltage (LV). Less than or equal to 1 kV.

Medium voltage (MV). Voltage greater than 1 kV but less than or equal to 35 kV.

P_{lt}. Perception of light flicker in the long term. Long term is usually defined as a 2-hour interval.

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P_{st}. Perception of light flicker in the short term. Short term is defined as a 10-minute interval.

Point of common coupling (PCC). The nearest point on the power system where a potentially offending fluctuating electrical load could be sensed by a load sensitive to the fluctuation. In the absence of clear agreement on where the PCC is located, the PCC shall be defined as the point where the power system containing the fluctuating load attaches to PacifiCorp's power system.

Voltage fluctuation. A sudden and noticeable change in rms voltage level, usually caused by changing system loads. For example, a fluctuation from a voltage sag due to a large motor start is comprised of two changes.

5. Limits and Their Applications

The limits presented here apply to those portions of the power system where voltage fluctuations can be observed by other customers. These points are not only the portions of the power system to which customers are presently connected, but also locations to which other customers could eventually be connected (see the definition for PCC above). The utility shall not be expected to design or build a system to handle excessive voltage fluctuations caused by customer equipment. It is important for customers to realize that these limits exist to protect all customers' quality of service and the operability of their equipment. Good service quality requires cooperation between the utility and the customers.

The guidelines in this document are comprised of four limits: (1) flicker, (2) infrequent events, (3) magnitude-duration, and (4) bounded magnitude. All four limits apply. These limits are to be used as guidelines only - references upon which good judgment should be based. These limits apply only to voltage fluctuations caused by events such as motor starting, fluctuating loads and system switching, not to steady-state voltage levels.

5.1. Flicker Limits

"Voltage flicker" does not actually exist, though this term is often heard. When lamps produce fluctuating light levels, and this is recognized by someone, we call this, "light flicker," or simply, "flicker." Flicker can be produced either by a problem in the light source or a fluctuation in the source voltage. If someone complains of flicker, and it is caused by voltage fluctuation, then its cause needs to be found. Sometimes flicker is caused by load fluctuations in the customer's equipment near the flickering lamp. Such problems can often be easily solved. If not, investigation must be taken beyond the meter into the utility system. This usually dictates that the flicker must be objectively measured.

5.1.1. Flicker Meter

Flicker produced by fluctuating source voltage is measured indirectly by a flicker meter. The modern flicker meter measures voltage fluctuation and infers light flicker by taking into account the following: how often the voltage fluctuation occurs, how abruptly the voltage fluctuates, the kind of lamp, the sensitivity of the eye to light, and the brain's perception. All of these factors are modeled in a modern IEEE 1453 compliant flicker meter (this measurement is more complex than simply measuring voltage fluctuation and frequency).

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Fortunately, despite its internal complexity, an IEEE flicker meter's output is simple: if the output is greater than 1.0, the flicker is generally irritable to humans; if less than 1.0, it is not. These results have been successfully validated with many years of real-world testing in several countries. The flicker meter's main output is in a unit called P_{st}, meaning, "Perception of light flicker in the short term."

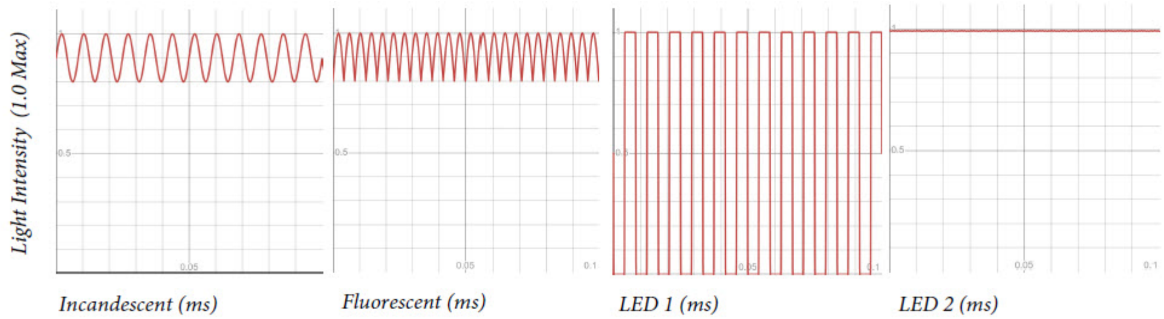

Figure 1—Light Output Variability of Incandescent, Fluorescent, and LED types (1 and 2), Left to Right

Light output of different lighting types vary greatly, see Figure 1. The features of incandescent and fluorescent ensure that the light intensity is always greater than 80% of its maximum output. The pulsing light intensity is the basis of the statistical analysis for IEEE 1453. EPA regulation has pushed for the discontinued use of incandescent lights. As a result of this regulation LED lighting will be ubiquitous in residential areas.

LEDs vary in quality of lighting more than incandescent or fluorescent lights. If the light flicker levels are below 1.0 Pst but the light flicker is still objectionable then exchanging lighting may be the solution. Low quality LEDs pulse light at 120 times a second, an example of the light output is LED 1. Higher quality LEDs produce a constant light source such as LED 2. Voltage variations applied to LED 1 can exaggerate the perception of light flicker. A light intensity drop of one of the square wave pulses results in a flicker tripled in duration. As the LED is not emitting light on either side of the square wave pulse a person will perceive longer flicker event. If flicker measurements are within company limits but the light flicker is stillobjectionable, exchanging pulsing LEDs for constant light source LEDs may be a solution.

Planned load characteristics should be obtained directly from the customer or equipment manufacturer. Gathering data for existing fluctuations requires the use of a recording voltmeter having a time resolution smaller than the occurrence of the flicker. Many recording voltmeters do not have sufficient resolution to perform this task.

5.1.2. Flicker Measurement Method

It is PacifiCorp's policy to measure flicker with an IEEE 1453 compliant flicker meter at the PCC. Such flicker meters shall have passed an internationally-accepted test protocol known to qualify digital flicker meters in real-world testing in the range of $0.2 < P_{st} < 4.0$. Since flicker often comes and goes, and human irritation to flicker is subjective, there is an objective methodology established by the IEEE for measuring with the flicker meter.

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5.1.3. Planning and Compatibility Levels

The IEEE concepts are intended to allocate allowable voltage fluctuation in a fair and equitable manner among fluctuating loads, and to ensure that these fluctuations do not adversely impact customers by causing noticeable light flicker. They are best understood by referring to Figure 2.

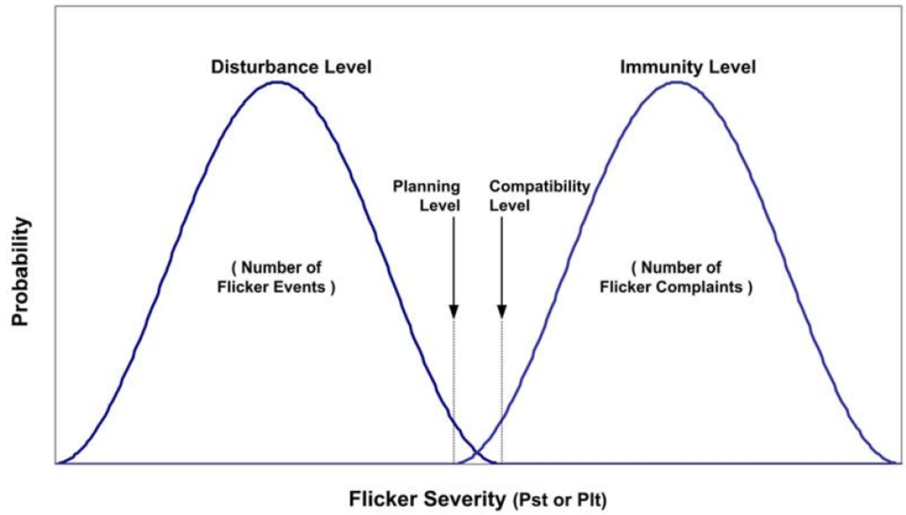

Figure 2—Probability of Flicker and Corresponding Levels

In this figure, there is a distribution of P_{st} levels at which flicker events typically occur. Collectively, they are called the "Disturbance Level". The probability of disturbances, or flicker events, typically peaks where P_{st} is at or below 0.5 in a power system unless there is a major flickering load nearby. At a transmission substation in a quiet area, P_{st} probability typically peaks around 0.2. The "Immunity Level" indicates the number of flicker-sensitive devices that would fail if the P_{st} level were that high. Or, perhaps more to the point, it can be viewed as the number of customer light flicker complaints that would be received if the P_{st} level were that high.

When a utility sets limits for flicker, it is appropriate to set a not-to-exceed level where only a very small number of customers would complain. This is called the "Compatibility Level" in Figure 2. Under most conditions, this level would rarely be exceeded. In order to plan a power system such that exceedance of Compatibility Levels would indeed be rare, a "Planning Level" is set below the Compatibility Level. At the Planning Level, no customer complaints for flicker should be received. Also, the Planning Level is set more conservatively because it is intended for higher power system voltages where the power system's capacity to absorb flicker events can be shared among multiple large fluctuating loads. This is sometimes called "having flicker margin."

5.1.4. Specific Flicker Limits

It is PacifiCorp's policy that flicker events caused by fluctuating voltage under any load on its power system shall not exceed the P_{st} or P_{lt} values shown in Table 1 as measured at the

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PCC within the statistical guidelines of Section 5.1.5. These limits are the same as the limits in IEEE 1453.

Table 1—Flicker Compatibility and Planning Levels

	Compatibility Levels	Planning Levels	
Voltage Level	LV & MV	MV	HV & EHV
P_{st}	1.0	0.9	0.8
P_{lt}	0.8	0.7	0.6

Please note in Table 1 that only MV events have both a Compatibility Level and a Planning Level. This means that individual compatibility problems between existing LV and MV customers are resolved at the P_{st} = 1.0 level, and future MV installations are more conservatively planned for the P_{st} = 0.9 level. Specific tools for planning are found in IEEE 1453.1. When very large new fluctuating loads are planned, these tools may be used by planners to evaluate requirements for the new loads.

P_{lt} was conceived to provide a longer-term view of flicker, typically two hours. This is appropriate for two situations: (1) when multiple fluctuating loads must be considered and these loads require a longer measurement interval for their combined flicker characterization, and (2) when one fluctuating load – such as an arc furnace – has a melt cycle that spans several ten-minute P_{st} intervals.

When P_{lt} is used, it should be calculated every ten minutes using a sliding interval over the last two hours. The advantage of using P_{lt} is that it provides a more stable output for flicker than does P_{st}. Especially when following the IEEE protocol of a one-week measurement session for flicker, reading a P_{lt} plot is much easier than reading a P_{st} plot.

5.1.5. Statistical Guidelines

The IEEE methodology allows the flicker limits of Table 1 to be exceeded a small percentage of the time. This section discusses how large this percentage can be. Generally, it is agreed that limits can be exceeded between 1% and 5% of the time over a one-week measurement period. For purposes of comparison, of the 1008 10-minute P_{st} intervals in a one-week period, a 1% excedance would allow 10 periods to exceed the limit. This is 1 hour and 40 minutes. A 5% excedance corresponds to 8 hours and 20 minutes.

If the times-of-day of exceedance were objectionable, such as during the evenings when many people had lights turned on in their homes, then the 1% limit would make more sense. If it were to be exceeded late at night when nearly all were sleeping, one would expect that the 5% limit would be more appropriate. In general, large flickering loads are held to the 1% exceedance limit, especially if commitment for a nocturnal time-of-day of exceedance cannot be assured.

5.2. Infrequent Events

Use of a flicker meter is best suited to voltage fluctuation events that occur frequently, that is, more often than once per hour. For infrequent events, such as once-per-week large motor starts, the allowable voltage change from pre-event voltage seen at the PCC, shall be limited to 6% as an

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absolute maximum. A better guideline for events occurring once-per-day, or thereabouts, as measured at the PCC, is 5.0%.

In general, customers are allowed as much self-induced voltage fluctuation as they can tolerate. However, residential customers using whole-house air-conditioning or heat pumps (HVAC) would be well served to limit their own voltage fluctuations to 4%. Voltage fluctuations due to HVAC equipment starts as measured at the PCC (nearest point where a neighbor connects to the power system, such as the service transformer secondary) should be limited to 2.5%. Regardless of these limits, if the frequency of fluctuation is more often than one change per hour, the P_{st} flicker limits set forth in Section 5.1 take precedence if they can be accurately determined.

Mitigation for infrequent events is considered adequate when voltage fluctuations are controlled such that their magnitude is within the guidelines described earlier in this section, or their duration does not exceed two electrical cycles. If, however, this brief voltage fluctuation is severe in magnitude, such as a large impulsive transient, then notching limits (see Engineering Handbook section 1C.4.1.6) still apply.

5.3. Magnitude—Duration Limits

Most voltage fluctuations are short-lived. They are caused by load that draws current with an initial large peak magnitude which decays rapidly. Occasionally, however, the large current draw lasts for a long time. Common examples are tankless water heaters and large momentum motor start. In such a case, the guidelines in Section 5.2 might need to be further restricted in order to avoid adverse customer impacts. Also, in some instances, taking measures to reduce the voltage fluctuation magnitude will add to its duration. For more details, refer to IEEE 1453.

At present, no industry standards for magnitude-duration limits exist. A rule of thumb is to limit the duration of noticeable voltage fluctuation to less than ten seconds. For noticeable fluctuations lasting ten seconds or longer at a customer site, the magnitude of fluctuation should be 3% or less, regardless of frequency.

5.4. Bounded Magnitude Limits

Sometimes a voltage level that is near a steady-state voltage range boundary (see Engineering Handbook document 1C.2.1) can be an additional constraint to voltage fluctuation magnitude. A fluctuation could possibly push this voltage to a level objectionable to other customers. An example of this would be a motor start at a location with an already low, but still allowable, voltage. In this case, a six percent voltage drop fluctuation would likely cause very observable and objectionable effects to nearby customers.

In order to prevent such events from happening, the voltage fluctuations should stay within the limits imposed by ANSI range B, and should only briefly (no more than a few seconds) exceed the limits of ANSI range A (see Engineering Handbook document 1C.2.1).

5.5. Use of Older Limits

In the past, standards attempted to cover both flicker (more often than one change per hour in frequency) and less frequent voltage fluctuations. These were generally based on older magnitude-frequency diagrams such as “the old GE curve” as represented in IEEE 519 or IEEE

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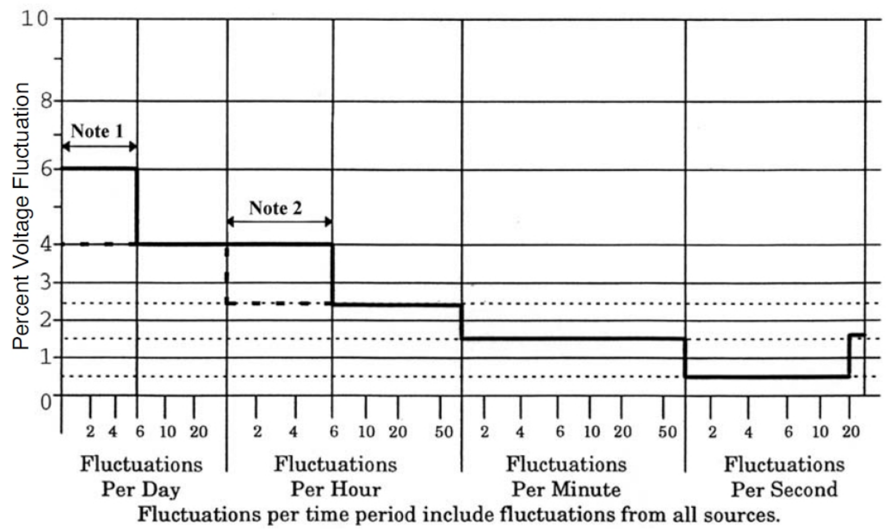
141. An older PacifiCorp standard described a stairstep emulation of these curves and extended them to cover less frequent voltage fluctuations. This is shown below as Figure 3. While this was a useful diagram that served well for many years, it left the reader with the impression that both the flicker limits and the infrequent fluctuation limits had the same scientific basis when, in fact, they didn't. Another problem in using this older diagram is that it cannot be effectively applied to non-rectangular or random voltage fluctuations.

It is PacifiCorp's policy that, lacking adequate modeling or measurement tools to predict or measure flicker in accordance with Section 5.1, limits shown in the older magnitude-frequency diagram (see Figure 3) may be used for guidance. However, for infrequent fluctuations (fewer than one voltage change per hour) Section 5.2 takes precedence over the limits shown in Figure 3.



Notes 1 and 2: During evening hours, use the next lower step.

Figure 3—Historic PacifiCorp Magnitude-Frequency Flicker Diagram

5.6. Customer Facility Limits

Customers are allowed as much self-induced flicker as they will tolerate, as long as their impact on other customers remains within the limits specified in Sections 5.1-5.4.

Adhering to these limits sometimes requires a voltage fluctuation study by a PacifiCorp engineer in the planning stage.

System models must often be prepared before a voltage fluctuation study can be performed. Customers should allow PacifiCorp sufficient time for a system impact study to be performed. PacifiCorp may charge the customer based on the complexity of the study. These studies are only valid for the information given at the time of the study. If the motor or load size changes, another study must be performed. Customers should understand that the purpose of these studies is to save them money on equipment while protecting the quality of service in their area. Their

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cooperation is essential. If a customer requires an immediate response, all loads listed below will require inrush mitigating equipment unless a voltage fluctuation study is performed:

1. Three-phase motors over 35 hp that are served from three-phase systems
2. Three-phase motors over 10 hp that are served from one- or two-phase systems (this includes motors served from phase converters.)
3. Single-phase motor over 3 hp served from a transformer that serves other customers
4. Any other load over 2 kVA that is highly variable in nature (examples: elevators, x-ray machines, arc welders, arc furnaces, and so forth.)

5.6.1. Commercial or Industrial Facilities

At commercial and industrial sites, the utility may not know if self-induced flicker will be greater than allowable limits if it does not affect other customers. This flicker can be a problem if sensitive loads exist on site. An example of this is a plant with an office attached in which light flicker is evident.

The utility should not be expected to install equipment to compensate for voltage fluctuations caused by on-site loads. The utility should install equipment necessary to serve the steady-state metered demand load of the facility. Generally, it is much more cost effective to reduce the effect of the voltage fluctuations by either modifying the offending load, or by conditioning the voltage supplied to sensitive equipment such as programmable controllers. Customers are responsible for providing the necessary equipment to make the installation meet their requirements.

To assist customers in identifying potential problems in their facilities, Table 2 indicates the sensitivities of some common devices to temporary low voltages.

Table 2—Equipment Undervoltage Sensitivities

Location of Voltage Drop Problem	Minimum Allowable Voltage (% of equipment rating)
At terminals of starting motor	80%[a]
All terminals of other motors that must re-accelerate	71%[a]
Ac contactor pick-up (by standard)	85%
Dc contactor pick-up (by standard)	80%
Contactor hold-in (average of those in use)	60-70%[b]
Solid-state control devices	90%[c]
Typical electronic equipment	80%
Metal halide or HP sodium lamp ballasts	90%

a. Typical for NEMA design-B motors only. Value may be higher (or lower) depending on actual motor and load characteristics.

b. Value may be high as 80% for certain conditions during prolonged starting intervals.

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c. May typically vary by ±5% depending on available tap settings of power supply transformer when provided.

5.6.2. Residential Facilities

Standard practice requires new residential systems to be in compliance with flicker limits. The following assumptions are made:

1. These limits apply at the point of delivery.
2. The utility should not have to compensate for unusually large impedance in the customer's facility.
3. Most customers will have a separate feeder from the panel for high-inrush loads.
4. As with industrial or commercial loads, the residential customer is responsible for mitigating self-inflicted problems caused by large fluctuating loads such as compressors or welders.

5.6.3. New Load Considerations

Voltage fluctuations can be quite costly to correct. Large new loads being connected to the distribution system have the potential to cause voltage fluctuation problems. When it is suspected that a proposed new load may cause excessive voltage fluctuations on the system, accurate data on the equipment and the load characteristics must be obtained from the equipment manufacturer. The customer and utility will work together to ensure the service quality in the area.

6. Conclusion

Following this guideline is not a guarantee of trouble-free voltage fluctuation. In some instances, a customer may be particularly sensitive to voltage fluctuations. If the cause can be easily mitigated for such a customer, then it should be done. If not, objective measurement equipment such as a flicker meter is required to determine a fair balance between one customer's sensitivity and another's need to fluctuate the voltage. It should be recognized that certain types of electrical equipment, such as some semiconductor fabrication equipment, are particularly susceptible to voltage fluctuations. However, it should also be recognized that no utility system can be entirely free of such fluctuations.

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