INTEGRAL energy

Power Quality Centre

University of Wollongong

Technical Note No. 7 **August 2003**

VOLTAGE FLUCTUATIONS IN THE ELECTRIC SUPPLY SYSTEM

This Technical Note discusses voltage fluctuations, their causes and adverse effects, what levels are acceptable and how to reduce their consequences. Integral Energy, your local Network Operator or the Integral Energy Power Quality Centre can give you additional advice if you have particular concerns with these issues.

Summary

Voltage fluctuations are defined as repetitive or random variations in the magnitude of the supply voltage. The magnitudes of these variations do not usually exceed 10% of the nominal supply voltage. However, small magnitude changes occurring at particular frequencies can give rise to an effect called lamp flicker. This term is used to describe the "impression of unsteadiness of visual sensation induced by a light source whose luminance or spectral distribution fluctuates with time" [1]. Flicker is essentially a measure of how annoying the fluctuation in luminance is to the human eye. Standards limit the magnitudes of starting currents and load fluctuations of equipment to control the level of voltage fluctuations. Where the levels of indices specified in the standards are exceeded, mitigation techniques to reduce the effects of voltage fluctuations are required.

Contents

1. What are voltage fluctuations?

Voltage fluctuations can be described as repetitive or random variations of the voltage envelope due to sudden changes in the real and reactive power drawn by a load. The characteristics of voltage fluctuations depend on the load type and size and the power system capacity. Figure 1 illustrates an example of a fluctuating voltage waveform. The voltage waveform exhibits variations in magnitude due to the fluctuating nature or intermittent operation of connected loads. The frequency of the voltage envelope is often referred to as the flicker frequency. Thus there are two important parameters to voltage fluctuations, the frequency of fluctuation and the magnitude of fluctuation. Both of these components are significant in the adverse effects of voltage fluctuations.

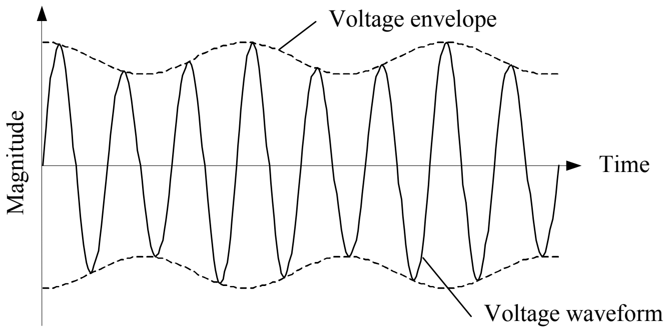

Figure 1 – Terminal voltage waveform of fluctuating load

In Figure 1 the voltage changes are illustrated as being modulated in a sinusoidal manner. However, the changes in voltage may also be rectangular or irregular in shape. The profile of the voltage changes will depend on the current drawn by the offending fluctuating load.

Typically, voltage changes caused by an offending load will not be isolated to a single customer and will propagate in an attenuated form both upstream and downstream from the offending load throughout the distribution system, possibly affecting many customers.

2. Effects of voltage fluctuations

The foremost effect of voltage fluctuations is lamp flicker. Lamp flicker occurs when the intensity of the light from a lamp varies due to changes in the magnitude of the supply voltage. This changing intensity can create annoyance to the human eye. Susceptibility to irritation from lamp flicker will be different for each individual. However, tests have shown that generally the human eye is most sensitive to voltage waveform modulation around a frequency of 6-8Hz. The perceptibility of flicker is quantified using a measure called the short-term flicker index, P_{st}, which is normalised to 1.0 to represent the conventional threshold of irritability.

The perceptibility of flicker, a measure of the potential for annoyance, can be plotted on a curve of the change in relative voltage magnitude versus the frequency of the voltage changes. Figure 2 illustrates the approximate human eye perceptibility with regard to rectangularly modulated flicker noting that around the 6-8Hz region fluctuations as small as 0.3% are regarded as perceptible as changes of larger magnitudes at much lower frequencies [1]. Figure 2 is often referred to as the flicker curve and represents a P_{st} value of 1.0 for various frequencies of rectangular voltage fluctuations. Although regular rectangular voltage variations are uncommon in practice they provide the basis for the flicker curve, defining the threshold of irritability for the average observer. It is worth noting that the flicker curve is based on measurements completed using a 60W incandescent light bulb. This is used as a benchmark measurement, however the perceptibility of lamp flicker will vary depending on the size and type of lamp used.

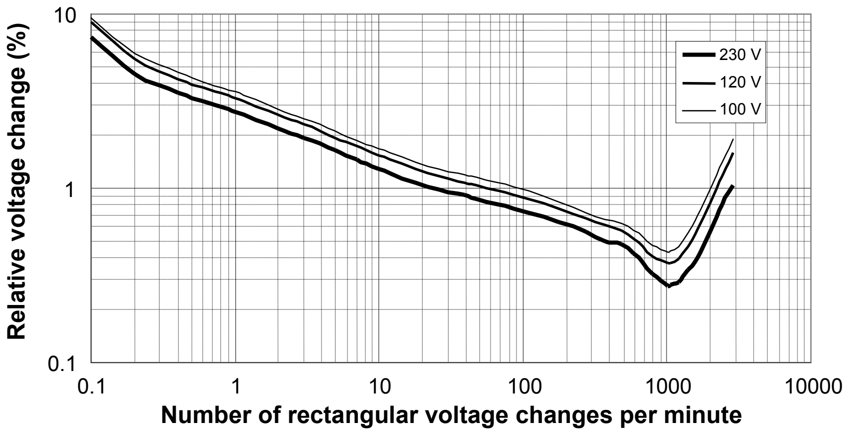

Figure 2 – Flicker curve for rectangular modulation frequencies [1]

Voltage fluctuations on the public low voltage power system are required to be within accepted tolerances specified in the standards. In general the acceptable region of voltage fluctuations falls below the flicker curve illustrated in Figure 2.

Voltage fluctuations may also cause spurious tripping of relays; interfere with communication equipment; and trip out electronic equipment. Severe fluctuations in some cases may not allow other loads to be started due to the reduction in the supply voltage. Additionally, induction motors that operate at maximum torque may stall if voltage fluctuations are of significant magnitude.

3. Causes of voltage fluctuations

Voltage fluctuations are caused when loads draw currents having significant sudden or periodic variations. The fluctuating current that is drawn from the supply causes additional voltage drops in the power system leading to fluctuations in the supply voltage. Loads that exhibit continuous rapid variations are thus the most likely cause of voltage fluctuations. Examples of loads that may produce voltage fluctuations in the supply include

- Arc furnaces
- Arc welders
- Installations with frequent motor starts (air conditioner units, fans)
- Motor drives with cyclic operation (mine hoists, rolling mills)
- Equipment with excessive motor speed changes (wood chippers, car shredders)

Often rapid fluctuations in load currents are attributed to motor starting operations where the motor current is usually between 3-5 times the rated current for a short period of time. If a number of motors are starting at similar times, or the same motor repeatedly starts and stops, the frequency of the voltage changes may produce flicker in lighting installations that is perceivable by the human eye.

Consider the simple model representing a fluctuating load drawing real power P, and reactive power Q, connected to a power system with an impedance of resistance R, and reactance X, as illustrated in Figure 3. The voltage V_R seen by the customer can usually be regulated by operating the system voltage V_S at a slightly higher value to ensure V_R remains at the required value, e.g. 230V for a single-phase system. During steady state operation this can be achieved through the use of automatic tap changers on transformers, line drop compensators and voltage regulators. For more rapid changes in load current the operation of such devices is not fast enough in response to effectively regulate the voltage to stay at the required value.

The resultant voltage due to the current drawn by the load is illustrated in the phasor diagram of Figure 4 where V_S is the supply voltage and V_R is the resultant voltage seen by the load at the point of common connection (PCC).

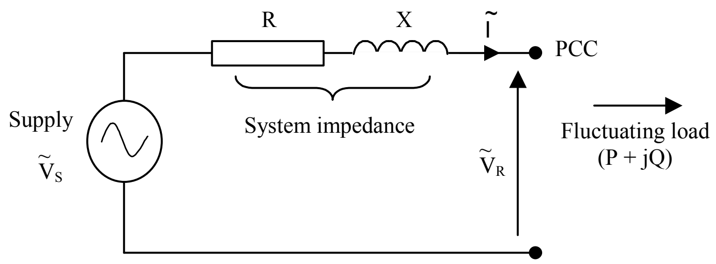

Figure 3 – Simple model of power system

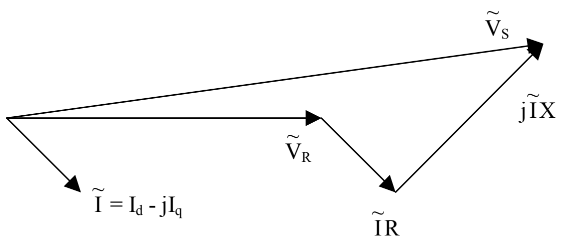

Figure 4 - Phasor diagram of supply voltage

The complex power drawn by the fluctuating load and the voltage phasors can be described by equations (1) and (2) respectively.

$$\tilde{V}_R \tilde{I}^* = P + jQ \qquad (1)$$

$$\tilde{V}_S = \tilde{V}_R + \tilde{I}(R + jX) \qquad (2)$$

Expanding equation (2) for the voltage phasors provides the following

$$\tilde{V}_S = \tilde{V}_R + (I_d - jI_q)(R + jX) \qquad (3)$$

$$= (V_R + R\,I_d + X\,I_q) + j(X\,I_d - R\,I_q) \qquad (4)$$

Ignoring the phase differences between V_R and V_S in equation (4) and equating only the real parts

$$V_S = V_R + R\,I_d + X\,I_q \qquad (5)$$

Assuming V_S is a very strong supply system, i.e. V_S remains constant regardless of the current drawn by the fluctuating load, for any changes in I_d and I_q the changes in V_R will be as follows

$$0 = \Delta V_R + R\,\Delta I_d + X\,\Delta I_q \quad (6)$$
$$\Delta V_R = -(R\,\Delta I_d + X\,\Delta I_q) \quad (7)$$

Equation (7) can be re-written in per unit, i.e. in terms of the changes in real and imaginary power drawn by the fluctuating load

$$\Delta V_R = -(R\,\Delta P + X\,\Delta Q) \quad (8)$$

If R is negligible, then the reactance X = 1 / Fault level, leading to equation (9)

$$\Delta V_R = -\Delta Q / \text{Fault level} \quad (9)$$

Thus, it can be seen that the voltage at the point of common connection is essentially a function of the reactive power variation of the load and supply system characteristics. Note that for low voltage systems where R is considerably larger the real power may also contribute significantly to voltage variations.

4. Calculation of flicker indices

There are two major indices used in the evaluation of flicker in power systems, the short-term flicker index, P_{st} as stated before, and the long-term flicker index, P_{lt}. The P_{st} index represents the perceptibility of flicker based on a criterion that flicker levels created by voltage fluctuations will annoy 50% of population. This index is calculated on a 10-minute basis to evaluate short-term flicker levels. For a periodic rectangular voltage fluctuation, this index, normalised to a value of 1.0, is illustrated in Figure 2 as the flicker curve.

Calculation of P_{st} values is performed by a flickermeter. The design specification and functionality of a flickermeter is outlined in Australian standards AS 4376 and AS 4377. Figure 5 illustrates the functional block diagram of a flickermeter as per the standards. The first three blocks of the design perform the signal conditioning operation on the measured voltage waveform v(t). More specifically these blocks represent how the voltage fluctuations are transformed to light fluctuations, determine the perceptibility to the human eye and then simulate the brain response (annoyance) to lamp flicker. This process is often referred to as the "lamp-eye-brain" response. The final block performs the statistical analysis required to calculate P_{st} and P_{lt}.

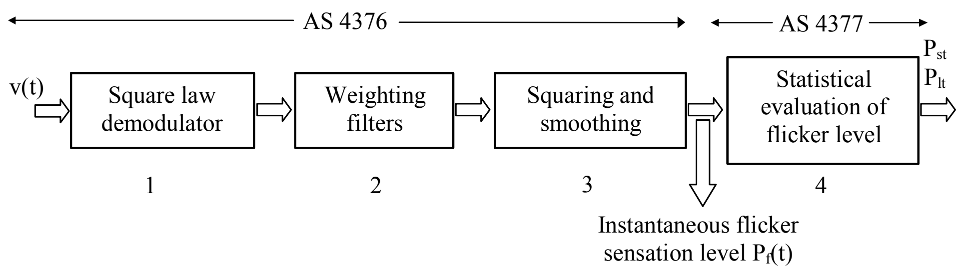

Figure 5 – Functional block diagram of a flickermeter

The filtering (smoothing) and weighting in the first three blocks of the flickermeter adjust the fluctuation frequency components according to the perceived human annoyance. The output of the signal conditioning blocks may look similar to that illustrated in Figure 6 for a single 10-minute interval.

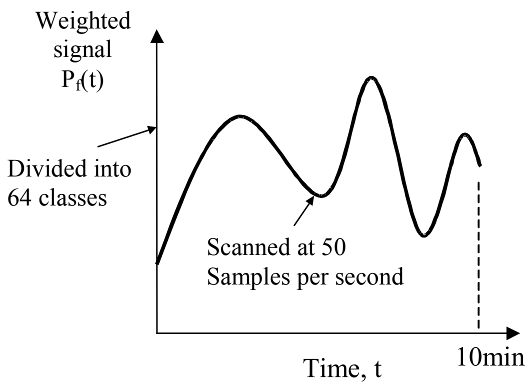

Figure 6 – Output of flickermeter at the 3rd block

The output of the 3rd block of the flickermeter, the instantaneous flicker level signal, is sampled and divided into 64 different time-at-level classifications. This allows a statistical evaluation of the flicker levels to be established. The measure of the severity of short term flicker, P_{st} is then calculated every 10 minutes using weighted cumulative probability values of the flicker levels exceeding 0.1, 1, 3, 10 and 50% of the time using equation (10).

$$P_{st} = \sqrt{0.0314\,P_{0.1} + 0.0525\,P_1 + 0.0657\,P_3 + 0.28\,P_{10} + 0.08\,P_{50}} \qquad (10)$$

People's tolerance to flicker over longer periods is less than for the short term. For this reason the second index is introduced by the standards, the long-term flicker index, P_{lt}. P_{lt} is an average of P_{st} values evaluated over a period of two hours using a cubic law as defined in equation (11).

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum P_{st}^3} \qquad (11)$$

As a short-term flicker index of 1.0 suggests that the sensation of flicker will be annoying to the human eye, utilities must ensure that flicker levels arising as a result of voltage fluctuations remain below 1.0. For the long-term flicker index the values should be kept even lower as long-term flicker is generally more annoying to customers.

5. Voltage fluctuation standards and planning levels

5.1 AS 4376 and AS 4377

AS 4376 and AS 4377 cover the functionality and design of a flickermeter. A flickermeter may be a stand-alone device or, as is usually the case, incorporated as part of the functionality of a multipurpose power quality monitoring device.

AS 4376 includes design specifications of a flickermeter capable of indicating light flicker perception due to all practical voltage fluctuation waveforms. This standard also includes type test specifications for compliance with

- Rectangular and sinusoidal voltage fluctuations (for specified frequency and percentage change in voltage), and
- Environmental tests such as EMC and climatic tests.

AS 4377 provides details for the statistical evaluation methods for both short-term and long-term flicker severity. The statistical analysis emulates the perception of the lamp-eye-brain chain providing the quantified outputs P_{st} and P_{lt}. Calculations are completed on-line resulting in P_{st} values for each 10-minute interval and P_{lt} values using the cube law every two hour interval.

5.2 AS/NZS 61000.3.3

AS/NZS 61000.3.3 specifies the emission limits for low voltage equipment rated less than or equal to 16A to ensure excessive voltage fluctuations are not caused by their normal operation. The standard outlines the test conditions for type tests on the equipment (cookers, lighting equipment, washing machines, tumbler dryers, refrigerators, copying machines, laser printers, vacuum cleaners, food mixers, portable tools, hair dryers, consumer electronics, direct water heaters).

To measure voltage fluctuations caused by the operation of specific loads the magnitude of change in the rms voltage is considered every half cycle (10ms) of mains frequency for all the rms values of voltage over each 10-minute interval. The voltage change characteristics $\Delta V(t)$ shown in Figure 7 is then determined for periods between when the voltage has been in steady state for at least one second. A reference system impedance is specified to be used during the type tests.

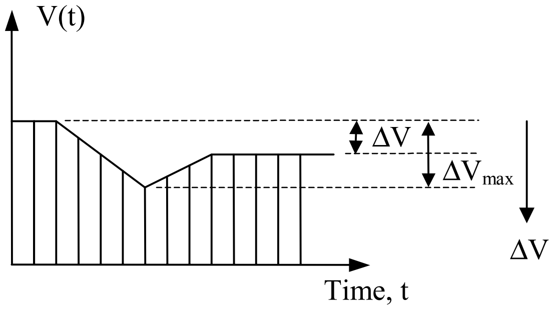

Figure 7 – Histogram evaluation of $\Delta V(t)$

5.3 AS/NZS 61000.3.5

AS/NZS 61000.3.5 covers the specifications outlined in AS/NZS 61000.3.3 for low voltage equipment with rated current greater than 16A. This standard differs however in that it uses the actual point of connection to perform the compliance tests rather than a reference impedance. Thus to perform the evaluation of this equipment the consumer and electricity supplier must cooperate and provide the necessary data to allow an evaluation to take place. Such data may include load details, system impedance, existing level of disturbance, and cost of power supply improvements.

5.4 AS/NZS 61000.3.7

The Australian standard which specifies the limits for "fluctuating loads in MV and HV power systems" is based on the IEC report of the same name, IEC 61000-3-7:1996. This IEC report is a Technical Report – Type 3, meaning it does not have the same standing as an international standard but may be referred to for assistance in setting limits for customers. However in Australia this document has been adopted as a standard. This standard is required to ensure the interaction of all loads connected to the power system does not cause excessive voltage fluctuations. Each customer is allocated certain limits to ensure the impact of the operation of their loads is acceptable with regards to flicker.

The primary objective of this standard is to provide guidance for engineering practices. The given guidelines are based on certain simplifying assumptions and hence recommended approaches are to be used with flexibility and judgement. The final decision for connection of a customer's fluctuating load will always rest with the electricity supplier.

Compatibility levels for voltage fluctuations are set as shown in Table 1 for the short-term and long-term flicker indices. Utilities should endeavour to ensure flicker indices do not exceed the compatibility levels recommended by the relevant standards. For this reason utilities should allocate planning levels below the compatibility levels. The planning levels for MV and HV systems recommended in the standard are given in Table 2.

Table 1 - Compatibility levels for LV and MV systems

P_{st}	1.0
P_{lt}	0.8

Table 2 - Planning levels for MV and HV and EHV systems

	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

The general procedure for evaluating fluctuating loads as per the AS/NZS 61000.3.7 standard is completed in stages. Stage 1 is a simplified evaluation of disturbance emission. If the fluctuating load or the customers maximum demand is small compared to the short circuit capacity at the point of common connection, no detailed evaluation is necessary. Stage 2 calculates emission limits proportional to maximum demand. Equipment is evaluated against system absorption capacity that is allocated to individual customers according to their demand. Absorption capacity is derived from planning levels. In allocating to individual customers at MV levels, disturbances derived from HV levels should be considered. The final stage is acceptance of higher emission levels on an exceptional and precarious basis where utility and consumer may agree on the connection with special conditions.

5.5 AS/NZS 61000.3.11

This standard covers the conditional connection of loads that come under the specifications outlined in AS/NZS 61000.3.5 but do not meet compliance.

6. Reducing the effects of voltage fluctuations

To allow equipment connected to the power system to operate correctly it is important for both the utility and their customers to ensure that the operating voltage of the system remains within the boundaries set by the appropriate standards. As mentioned previously power system equipment does not usually provide adequate response time for mitigation of rapid voltage changes. It is inherent that complete compensation of flicker is not possible [7]. However, the magnitude of the voltage fluctuations may be reduced using one of the following network strategies

- Increasing the fault level at the point of connection. Strengthening the system or reconnecting the offending load at a higher voltage level can achieve this.
- Decrease the reactive power flow through the network due to the load. This may be achieved through the use of a Static VAr Compensator (SVC) and will help reduce voltage sags.
- Strengthening the network reactive power compensation. A larger number of smaller capacitor banks distributed throughout a system will allow finer tuning of reactive power requirements [7].

Frequent motor starting has been highlighted as a significant cause of flicker. This is especially significant for larger single-phase air conditioner compressor motors connected to weak low voltage distribution systems. In order reduce the magnitude of voltage fluctuations a reduction in the starting current of a motor must be accomplished. This can be achieved through the use of various starting techniques. [7] suggests the use of the following motor starting techniques

- Inclusion of an intermediate star-delta resistance-delta starting configuration for three-phase motor applications.
- Installing a series resistance or inductance with the motor stator to effectively apply reduced voltage starting.
- Use of an exclusive autotransformer matched to the design of the motor.
- Soft start using power electronic soft starters.
- Full inverter control of motor. This has the advantage of controllable speed and torque providing efficient motor operation.

As frequency is also an important parameter of voltage variations a reduction in the number of motor starts may also lessen the effects of flicker. This may be achieved through coordinated control of motors or by providing sufficient storage of heat for the case of air conditioners and heat pumps [8].

7. References and additional reading

1. AS/NZS 61000.3.3:1998, “Electromagnetic compatibility (EMC) Part 3.3: Limits – Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current less than or equal to 16A”, Australian Standards, 1998.
2. AS/NZS 61000.3.5:1998, “Electromagnetic compatibility (EMC) Part 3.5: Limits – Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current greater than 16A”, Australian Standards, 1998.
3. AS/NZS 61000.3.7:2001, “Electromagnetic compatibility (EMC) Part 3.7: Limits – Assessment of emission limits for fluctuating loads in MV and HV power systems”, Australian Standards, 2001.
4. AS/NZS 61000.3.11:2002, “Electromagnetic compatibility (EMC) Part 3.11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current less than or equal to 75A and subject to conditional connection”, Australian Standards, 2002.
5. AS/NZS 4376:1996, “Flickermeter – Functional and design specifications”, Australian Standards, 1996.
6. AS/NZS 4377:1996, “Flickermeter – Evaluation of flicker severity”, Australian Standards, 1996.

7. Iglesias et al, "Power Quality in European electricity supply networks", 1st Edition, Euroelectric, Brussels, 2002.
8. Morcos and Gomez, "Flicker sources and mitigation", IEEE Power Engineering Review, November 2002.

8. Integral Energy Power Quality Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. The Centre's objective is to work with industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the control of distortion of the supply voltage, training in power quality issues at all levels, and specialised consultancy services for solution of power quality problems. You are invited to contact the Centre if you would like further advice on quality of supply.

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