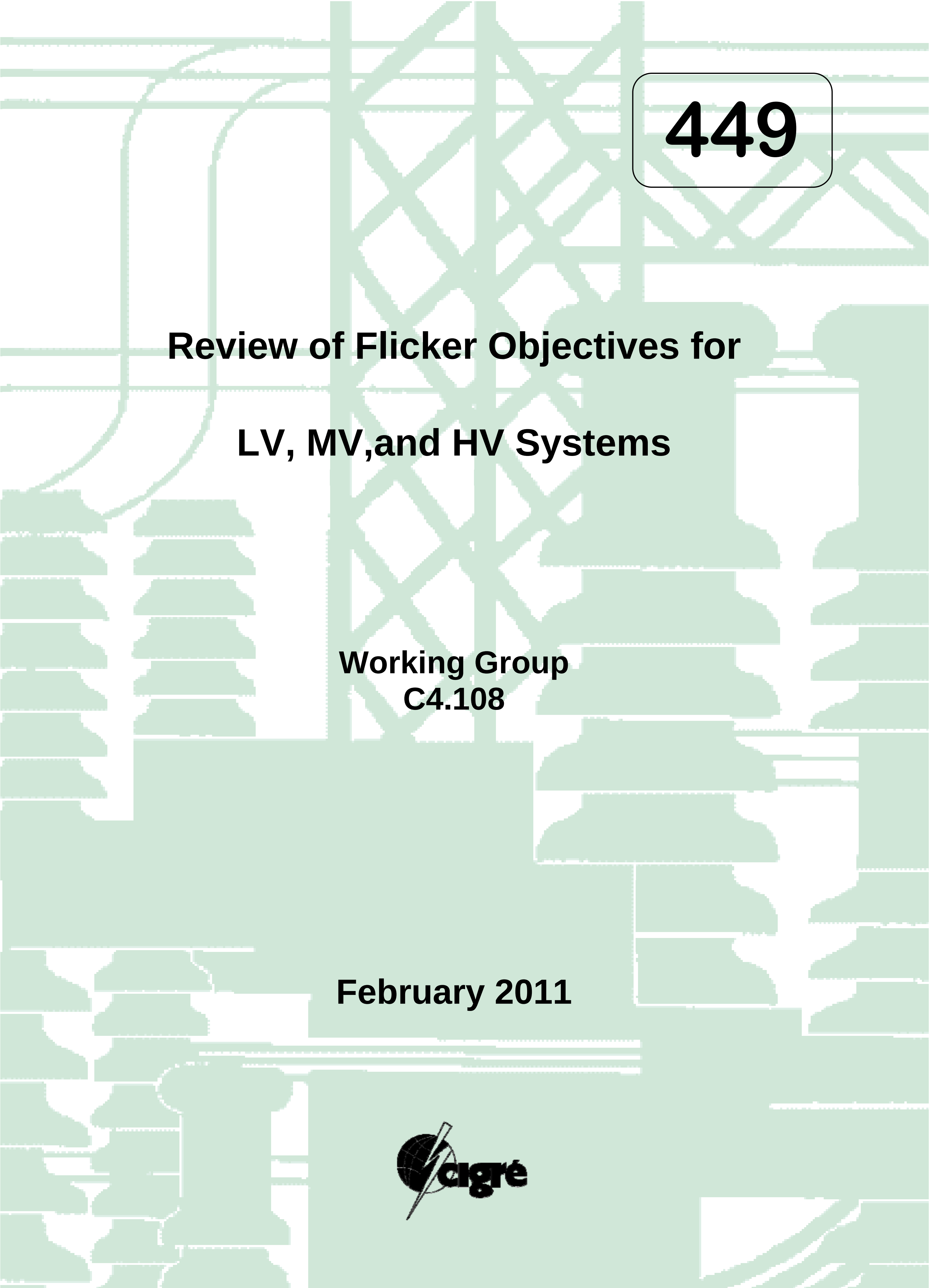

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Review of Flicker Objectives for LV, MV,and HV Systems

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1. Introduction

Voltage fluctuations and flicker have been assessed for many years using the internationally-recognized concept of short-term flicker severity, P_{st}. Compatibility levels for voltage fluctuations have been specified at low voltage based on the fact that $P_{st} = 1$ corresponds to the point above which the majority (>50%) of network (LV) users would be expected to complain. Large numbers of both anecdotal and formally documented cases have shown that measured flicker levels often far exceed voltage-level appropriate planning levels derived from the established compatibility levels without the expected complaints from low voltage users. Major objectives of this report are to

(1) assess and document these cases,
(2) evaluate why such poor correlation apparently exists, and
(3) to present methods and techniques which could result in improved correlation.

A fourth related objective is to summarize existing practices regarding rapid voltage changes and make recommendations for improvements.

A large body of measurements and associated complaints regarding flicker was accumulated as a part of the recently-completed work of CIGRE/CIRED JWG C4.07. This report takes some of these results and includes additional cases made available to this WG. The following observations apply consistently to the majority of the cases:

- Measurements are usually made at HV or EHV points of evaluation;
- Measured levels often significantly exceed planning levels;
- Sufficient cases with long-term measurements are available to assume complete coverage of various installation operating modes, times of day, and other variations; and
- Network events, such as faults, may well lead to voltage disturbances which may or may not be removed from a flicker measurement set.

Based on the cases reviewed, two significant hypotheses regarding the poor measurement/complaint correlation are put forward in this report. These hypothesis appear to fit the majority of the cases and can be well-supported by independent theoretical and laboratory investigations. The hypotheses are:

- Measurements are made at HV/EHV system locations whereas observers potentially subjected to intolerable flicker levels are located at LV. Significant reduction in flicker levels between HV/EHV and LV locations should be expected based on network effects and load response. This reduction is documented in this report based on theoretical, laboratory, and field test results.
- Markedly greater voltage fluctuations are required for modern lighting to produce the same light output variations as the 60 W incandescent lamp upon which the entire P_{st} concept is based. Therefore, it is possible that P_{st} measurements at LV locations could exceed the compatibility levels based on incandescent lamps without leading to flicker complaints when modern lighting is in use.

Considering these two hypotheses, methods for improving the correlation have been documented. These methods concentrate largely on improving the manner in which flicker reduction throughout a system is taken into account when planning levels at

HV/EHV are specified so as to maximize electromagnetic compatibility (EMC) with regard to the compatibility level at LV. While it is also possible to consider changing the compatibility level at LV to more accurately account for modern lighting, this approach is not recommended in this report because other LV (non-lighting) equipment could possibly be more sensitive than modern lighting. Evaluation of the immunity levels of the wide-range of LV equipment was beyond the scope of this WG, so no recommendations can be made in this report regarding modifying LV compatibility levels.

While not typically considered as flicker, so-called rapid voltage changes are also addressed. In this report, the existing definitions, standards, and assessment methods are summarized and it is clear that there are inconsistencies across the IEC 61000 series. Uniform definitions are lacking and no clearly-defined measurement methods or assessment indices exist. Furthermore, the compatibility levels established at LV and MV are generally vague in nature and not overly suitable for the derivation of planning levels. As a result and as documented in this report, industry practice regarding rapid voltage changes varies widely and is not necessarily consistent with any existing standard or guide. However, recent research in this area has led to the proposal of new indices for quantifying rapid voltage changes in a defined manner. These indices and sample field test results are documented in this report.

2. Correlation of P_{st} Levels With User Complaints

2.1. Introduction

Comparing flicker planning levels and flicker requirements given by utility companies world wide, it can be found that there are significant differences in these planning levels and thus in requirements to installations which have installed flicker generating equipment such as arc furnaces, welders, etc. Installations which include large equipment with unsteady operational behavior like steel plants with electric arc furnaces are usually supplied by medium or high voltage lines. Thus for system owners or operators, these plants are medium or high voltage installations that have to fulfill special requirements regarding power quality because their equipment is able to cause voltage variations in the supply networks which could be transferred via the point of common coupling (PCC) into the low voltage busses which are supplying residential customers. In these low voltage busses, voltage fluctuations can create disturbing light flicker. However, the PCC is often located in the high voltage portion of the supply network and it is at this location that an installation has to insure that its emission limits for flicker, harmonics, and other disturbances are not exceeded.

Taking into account that the flicker immunity of equipment connected to LV systems and the flicker sensitivity of residential customers are more or less equal in a globalized world, one should expect that the planning levels used to derive emission limits do not significantly differ worldwide. In reality, there are significant differences in the flicker planning levels and flicker requirements given worldwide by system owners or operators to the installations which they supply. If extremely low planning levels are fixed in standards or used to derive emission limits given by system owners or operators to installations in certain areas, such installations could be placed at a significant competitive disadvantage.

One general indicator that equipment may generate intolerable flicker at the PCC is the ratio of the equipment power to the short circuit power at the same location. Because of this dependence, smaller furnaces, welders, or other fluctuating equipment are able to cause severe flicker problems. Therefore, the decision of which planning levels to adopt and the subsequent derivation of emission limits has the potential to affect many users of a network at a variety of voltage levels.

The purpose of this chapter is to compare international planning levels for flicker in high voltage networks and to show that there are remarkable differences. Besides this, flicker requirements (i.e., emission limits) which were recently given by the responsible system owner or operator to installations running flicker generating equipment will be compared. Furthermore, flicker measurements will be used to show that there are cases in which the measured flicker values in high voltage networks are much higher than the common planning levels given in various standards while no flicker complaints are received from other network users. It is this evidence of poor correlation between measurements and complaints which suggests that either the overall strategy for EMC regarding flicker could be improved or the associated compatibility levels should be reviewed. Chapters 3 and 4 of this report address these issues in detail.

2.2. Examples of International Flicker Requirements in High Voltage Networks and Real World Measurements

2.2.1. Planning Levels

Planning levels given by international and national standards or by network owners or operators can differ very much from each other although all are using the same flicker definition given by either the IEC 61000 series or the Japanese standard (i.e. ΔV_{10}). For flicker measurement, two basic indices are used: P_{st} and P_{lt}. The P_{st} (st = short term) value is determined after a measurement interval of 10 min. The long term flicker value P_{lt} (lt = long term) is normally calculated using 12 consecutive short term flicker values and represents a time interval of 2 hours. The flicker measurements are usually done over a time period of one week because the P_{st} values usually differ very much from time interval to time interval. A specified percentage of the measured values (e.g. 95% or 99%) have to be below the contracted emission limits. This is indicated by additional indices, i.e. P_{st99}.

Some national standards or practices specify the measurement period and percentiles to be used. In this field, there may be significant differences between regions or countries. For example the Chinese standard [1] requires that "***In accordance with the IEC standard, the measurement for each evaluation of flicker quota requires at minimum one week, which is performed with a maximal probability value of 99%. Such a specification is practically hard to be implemented in the power grid. In light with this standard, the measurement of the flicker quota of*** P_{st} ***for one day (24 hours) is specified, which is performed with a maximal probability of 95%. For the*** P_{lt} ***quota, the set value shall not be exceeded as specified in principle.***"

There is another important method to measure voltage flicker, the Japanese ΔV_{10} – method [2]. In this case the values are determined on a minute-by-minute basis. The relevant value is the 4th highest after one hour. Comparative measurements between P_{stmax} values and ΔV_{10} (4th) give a ratio of 3 for arc furnace applications when used in combination with the common arc furnace flicker estimation procedure involving flicker factors, K_{st} [3]. This method is mainly used in Asia (Japan, Korea, and Taiwan).

To illustrate the variation in planning levels used world wide, some examples are shown in Table 2-1.

Table 2-1. Example Planning Levels [3]

Country / Standard	Planning Level	Remark(s)
Germany / Grid code (VDEW)	$P_{st} < 0.8$ $P_{lt} < 0.59$	Percentile not specified

Country / Standard	Planning Level	Remark(s)
United Kingdom / P28	$P_{stmax} < 1.0$ & $P_{ltmax} < 0.8$ for 132kV and below $P_{stmax} < 0.8$ & $P_{ltmax} < 0.6$ for above 132kV	Supersedes P7/2, P8, P9, P13/1 and P16
Russia / GOST 13109/97	$P_{st} < 1.3$	Percentile not specified
China / GB 12326-2008	$P_{lt} < 1.0$ for 110 kV and below $P_{lt} < 0.8$ for above 110 kV	
Korea (KEPCO)	$\Delta V_{10} < 0.45$	4th highest of 60 per hour
Japan	$\Delta V_{10} < 0.45$	4th highest of 60 per hour
Taiwan (TPC)	$\Delta V_{10} < 0.45$	4th highest of 60 per hour Can be less according to the number of furnaces connected
France / CART and CARD	$P_{lt} < 1$ for 20 kV and above (100% of time)	Official planning levels do not exist. Grid access contracts specify these requirements.
Brazil	<u>Acceptable</u> P_{st} (D95%) < 1.0/TF P_{lt} (W95%) < 0.8/TF <u>Needs Attention</u> P_{st} (D95%) < 2.0/TF P_{lt} (W95%) < 1.6/TF	P_{st} (D95%) is the highest of the seven P_{st} values (95th percentile) on day (D) in the weeklong (seven day) measurement P_{lt} (W95%) is the P_{lt} value (95th percentile) of the week (W) TF is the “Transfer Factor” from low to high voltage Values above “needs attention” are considered unacceptable
IEC 61000-3-7 2nd Ed.	$P_{st} < 0.9$ for MV $P_{lt} < 0.7$ for MV $P_{st} < 0.8$ for HV $P_{lt} < 0.6$ for HV	Indicative values (assumption that the transfer coefficient is unity) In practice, the transfer coefficients between different voltage levels are less than 1.0.

Country / Standard	Planning Level	Remark(s)
IEEE Std. 1453 [4]	$P_{st} < 0.9$ for MV $P_{lt} < 0.7$ for MV $P_{st} < 0.8$ for HV $P_{lt} < 0.6$ for HV	Adopted in USA in 2004. Modeled on IEC 61000 series. Limited use to date.

2.2.2. Correlation of Measurements with Complaints

Besides comparing planning levels on an international scale, the results of correlations between flicker measurements in high voltage networks and user complaints (from LV networks) can be compared. These examples show that in many cases the measurable flicker is higher than typical planning levels (and therefore higher than any derived emission limit) without creating intolerable disturbances leading to other user complaints.

In Table 2-2 are shown some examples of measured flicker levels in high voltage systems along with remarks regarding flicker-related complaints. It should be pointed out that all these measurements have not been taken to prove that the actual flicker levels could be higher than the planning levels (and derived emission limits). In general, other reasons have caused the authors to measure the flicker level and prepare a report.

Table 2-2. Examples of Measured Flicker Levels in High Voltage Systems

Country	Flicker source	Measured flicker values and voltage level	Remarks	Taken from reference:
Norway		132 kV $P_{st99} = 2$	Many complaints	[3]
Belgium	6 Furnaces	P_{st99} up to 1.7 (HV) P_{lt99} up to 1.19 (HV)		[5][3]
Spain	2 Furnaces	P_{st99} 1.7 P_{lt95} 1.20		[3]
Sweden	Industrial town	400 kV P_{st99} 1,59 145 kV P_{st99} 2.84	Some complaints	[3]
Ireland	Rolling mill	110 kV P_{st99} 1.05		[6]
Ireland	Arc furnace	110 kV P_{st99} 1.40		[7]
Italy	Arc furnace	220 kV P_{st99} 1.26		[8]

Slovenia	Arc furnace	110 kV P_{lt95} up to 2.8	Approximately 1 complaint per 1000 customers per year in a part of the LV network	
Australia	Arc furnace	132 kV P_{st95} 2.78 132 kV P_{lt95} 2.14 132 kV P_{st99} 3.10 132 kV P_{lt99} 2.23	No registered complaints	[9]
Austria	Arc furnace	110 kV P_{st99} 1.70 110 kV P_{st95} 1.42 110 kV P_{lt99} 1.63 110 kV P_{lt95} 1.33	Some complaints	
Brazil	2 arc furnaces	138 kV P_{stD95} 4.37 138 kV P_{ltW95} 3.66	No recorded complaints	
Survey F-7		site 1: 132 kV P_{st99} 1.25 site 2: 132 kV P_{st99} 2.60 site 3: 132 kV P_{st99} 1,62	No complaints Complaints Complaints	[10]
Surveys F-9-11		site 1: 110kV P_{lt95} 1.32	Complaints	[10]
Survey F-17	Arc furnace	130 kV P_{st95} 1.4 – 2.0	Complaints	[10]

2.3. Flicker Levels at HV/EHV, MV, and LV

A significant possible contributor to poor correlation between measured flicker levels and customer complaints is the fact that measurements are often made at HV and EHV levels whereas complaints are received from users observing LV lamp output. Significant attenuation, incorporated in [11] using transfer factors, is possible and indeed likely between HV/EHV and LV. Furthermore, modern lighting may be significantly less-sensitive to voltage fluctuations than standard incandescent lamps. Both of these topics are addressed in detail in later chapters. It is appropriate here, however, to demonstrate just how important these issues may be.

References [10] and [11] recommend transfer factors between HV/EHV and MV and MV and LV to be 0.8 and 1.0, respectively. Taking these factors into account together with recommended planning levels and an ultimate compatibility level of P_{st}=1.0 at LV, it is straightforward to show how P_{st} levels much greater than 1.0 (and therefore even greater than the recommended planning levels) can exist at HV/EHV.

As an example, consider a situation where the planning level at LV ($L_{P\mathrm{stLV}}$) is taken as the compatibility level, P_{st}=1.0. Assuming the global contribution of all LV loads ($G_{P\mathrm{stLV}}$) is

0.5 and the transfer coefficient between MV and LV systems ($T_{P\mathrm{stML}}$) is 1.0, the planning level at MV ($L_{P\mathrm{stMV}}$) can be derived as shown in (2-1).

$$\begin{aligned} G_{P\mathrm{stLV}} &= \sqrt[3]{L_{P\mathrm{stLV}}{}^3 - T_{P\mathrm{stML}}{}^3 \cdot L_{P\mathrm{stMV}}{}^3} \\ 0.5 &= \sqrt[3]{1^3 - 1^3 \cdot L_{P\mathrm{stMV}}{}^3} \\ L_{P\mathrm{stMV}} &= 0.96 \end{aligned} \tag{2-1}$$

Further assuming the global contribution of MV loads ($G_{P\mathrm{stMV}}$) is 0.5 and an HV to MV transfer coefficient ($T_{P\mathrm{stHM}}$) of 0.9, the allowable planning level at HV ($L_{P\mathrm{stHV}}$) can be derived as shown in (2-2).

$$\begin{aligned} G_{P\mathrm{stMV}} &= \sqrt[3]{L_{P\mathrm{stMV}}{}^3 - T_{P\mathrm{stHM}}{}^3 \cdot L_{P\mathrm{stHV}}{}^3} \\ 0.5 &= \sqrt[3]{0.96^3 - 0.9^3 \cdot L_{P\mathrm{stHV}}{}^3} \\ L_{P\mathrm{stHV}} &= 1.01 \end{aligned} \tag{2-2}$$

Continuing this process from HV to EHV assuming a global HV level ($G_{P\mathrm{stHV}}$) of 0.5 and an EHV to HV transfer coefficient ($T_{P\mathrm{stEH}}$) of 0.8 gives $L_{P\mathrm{stEHV}}$=1.21. This clearly demonstrates that flicker levels in excess of P_{st}=1.0 (the compatibility level at LV) can exist at HV/EHV without leading to any complaints from LV users. The key issues in this rationale are that flicker-producing loads may not be present at all voltage levels and that flicker levels are attenuated between voltage levels, particularly between HV/EHV and LV.

It is interesting to also consider how increased LV compatibility levels might impact the example calculations. If the same assumptions are used in each step of the process outlined in (2-1), (2-2), and all the way to EHV with an assumed LV compatibility level of P_{st}=1.1, the derived planning level at EHV becomes $L_{P\mathrm{stEHV}}$=1.38. Clearly this reasonably-derived level is far in excess of planning levels typically in use or those recommended in standard publications. Furthermore, planning levels in this range appear to be more in line with what may actually exist in terms of overall disturbance levels while still no complaints are received.

2.4. Conclusions

The examples given in this chapter document that flicker values in high voltage systems can be much higher than the usual planning levels and derived emission limits without causing complaints by residential users who are supplied via medium and low voltage from these systems. This fact is already taken into account by some system owners or operators but national and international standards and recommendations do not presently provide for such marked increases in recommended or indicative planning levels. Existing documents also may not address ways in which overall coordination approaches or compatibility levels could be modified. The remainder of this report contains significant discussion and analysis of possible changes to present practices which could be considered.

3. Influence of Non-Incandescent Lamp Technologies

3.1. Introduction

One possible reason for the apparently poor correlation between high flicker levels, as indicated by high P_{st} values, and customer complaints is associated with modern lighting technology. Since its inception, the flickermeter measurement method has been based on 60 W incandescent lamps and the responses of these lamps to input voltage fluctuations may be markedly different than responses of modern lighting. This chapter is intended to present the results of limited testing of modern lighting technologies so as to support the assertion that the lamp technology in use could play a significant role in flicker-related user complaints.

As countries adopt energy-saving measures related to lighting, including the elimination of incandescent lighting altogether (see Table 3-1 in which is presented an international summary of requirements related to lighting and the year in which they take (took) effect), the response of modern (more) energy efficient lamps to voltage fluctuations will play an increasingly large role in flicker investigations. It is, however, important to note that lamp flicker is just one possible EMC problem associated with voltage fluctuations. Other EMC situations may well exist or arise that result in voltage fluctuation compatibility levels, planning levels, and emission limits remaining essentially unchanged. These issues are considered to be beyond the scope of this report.

Table 3-1. Overview of Regulations & Policies Related to Incandescent and Energy-Efficient Lighting

Country or Region	Description	Year
Argentina	Banning of incandescents	2011
Australia	Banning of incandescents	2009
Canada	Banning of inefficient lighting	2012
European Union	Banning of incandescents	2012
Philippines	Banning of incandescents	2010
United States	Increase efficiency by 30%	2012-2014
Venezuela	Phase-out of incandescents	2005

Note: In most cases, legal actions taken or considered include reference to some minimum efficiency expressed in lumens/watt. Incandescent lamps are essentially banned by such requirements even if not explicitly specified.

Note: In all cases, regulations could change due to economic, political, or other factors. This table is intended as a summary of conditions at the time of publication of this report and includes both existing and proposed laws as well as documented intentions to develop such laws.

Note: In many cases, a number of exceptions and special applications exist such as for decorative lighting. This summary table is not intended to address all requirements in detail but rather to provide a global overview.

For flicker measurement, the well-known UIE/IEC flickermeter [2] [12] has been used widely in the world for many years. The short and long term flicker severity levels P_{st}

and P_{lt} can be obtained directly by using the UIE/IEC flickermeter. In Fig. 3-1 is shown the structure of the UIE/IEC flickermeter. It is composed of five blocks. A ‘lamp-eye-brain’ system, which contains 1) the response of a lamp to the supply voltage variation, 2) the perception ability of the human eye and 3) the memory tendency of the human brain [13], is imitated successfully by using a weighting filter, a squaring multiplier and a smoothing filter. However, the weighting filter used to simulate the relationship between light intensity and input voltage fluctuation, and how light intensity changes are sensed by the human eye, are based on sinusoidal voltage fluctuations applied to a coiled-filament gas-filled 230 V, 60 W or 120 V, 60 W incandescent lamp [2].

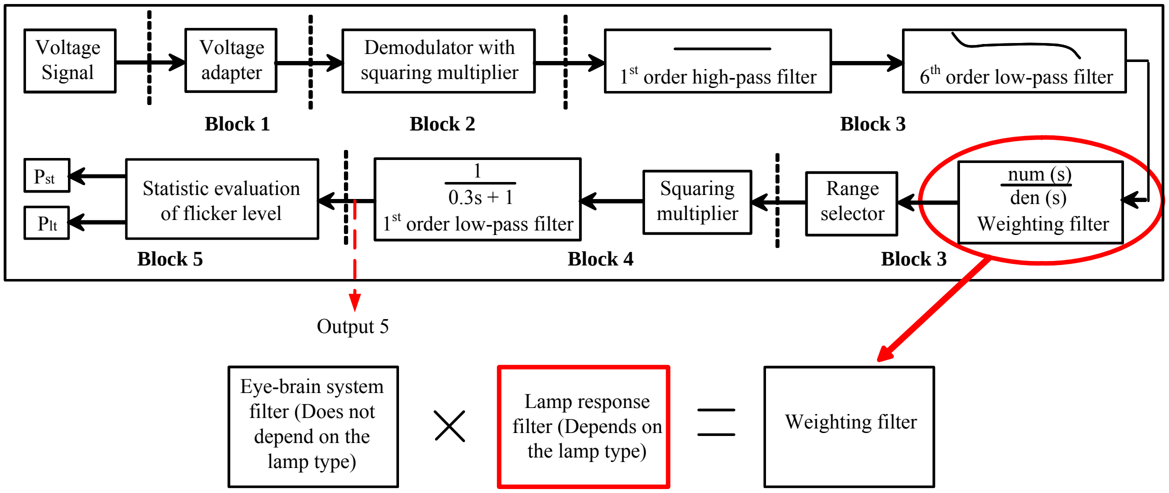


Fig. 3-1. The Structure of the UIE/IEC Flickermeter

Today, there are many different types of residential lamps in use in the market. Fluorescent lamps, compact fluorescent lamps, and halogen lamps are more and more popular in residential lighting. Due to different working principles of the different lamp types, the flicker responses of these lamps to voltage fluctuations are totally different. The flicker response measurements of different lamp types are given in Section 3.2 with the underlying physics of the operational principles of the various lamps described in Annex A.

3.2. Flicker Response of Different Types of Lamps

Because different lamp types have different working principles (see Annex A), the flicker response is different. The flicker responses of different lamp types determined using experimental tests are given in this section [14]. The tested lamps are:

- 60W glass incandescent lamp,
- 20W brilliantline pro tungsten halogen lamp,
- 15W four foot fluorescent lamp set (fluorescent tube with electronic ballast),
- 11W compact fluorescent tube with electronic ballast, i.e. energy saving lamp,
- 9W compact fluorescent tube (CFL) with magnetic ballast, and
- 3.4W LED lamp.

3.2.1. Mathematical Analysis of Measurement Results

All measurements mentioned in this section were done by applying a sinusoidal modulation voltage waveform. The light intensity of all lamp types depends on the electrical power consumed by the lamp. Thus, the illuminance of the lamp should be proportional to the electrical power consumed by the lamp. Under flicker conditions, the modulated voltage can be described as shown in (3-1).

$$\begin{aligned} v(t) &= A\cos(\omega t)\left(1 + m\cos\left(\omega_m t\right)\right) \\ &= A\cos(\omega t) + \frac{Am}{2}\cos\left(\omega t - \omega_m t\right) + \frac{Am}{2}\cos\left(\omega t + \omega_m t\right) \end{aligned} \tag{3-1}$$

In (3-1), ω is the fundamental radian (power) frequency of the voltage, ω_m is the voltage modulation radian frequency, and m is the per unit voltage modulation amplitude. Note that the modulation frequency is often considered in Hz due to industry familiarity with the units. In common practice and in most standards, $f_m = \omega_m / 2\pi$ is used.

The square of the modulated voltage is shown in (3-2).

$$\begin{aligned} v^2(t) = &\frac{A^2}{2}\left(1 + \frac{m^2}{2}\right) + \frac{A^2}{2}\left(1 + \frac{m^2}{2}\right)\cos\left(2\omega t\right) \\ &+ \frac{m^2 A^2}{8}\cos\left(2\omega t + 2\omega_m t\right) + \frac{m^2 A^2}{8}\cos\left(2\omega t - 2\omega_m t\right) \\ &+ \frac{mA^2}{2}\cos\left(2\omega t + \omega_m t\right) + \frac{mA^2}{2}\cos\left(2\omega t - \omega_m t\right) \\ &+ mA^2\cos\left(\omega_m t\right) + \frac{m^2 A^2}{4}\cos\left(2\omega_m t\right) \end{aligned} \tag{3-2}$$

If the lamp is assumed to be a linear load, the electrical power consumed by the lamp will be proportional to the square of the modulated voltage. Therefore, the electrical power consumed by the lamp will be a harmonic rich waveform instead of a perfect sinusoidal waveform. As the voltage modulation amplitude m is usually less than 0.1 per unit, the frequency components with frequencies (in Hz) of $2(f+f_m)$, $2(f-f_m)$ and $2f_m$ should be very small; they are usually neglected. The noticeable frequency components in the electrical power should be a dc component plus components with frequencies (in Hz) of $2f$, $2f+f_m$, $2f-f_m$ and f_m.

If the voltage fundamental frequency is 50 Hz and the modulation frequency is f_m, the instantaneous electrical power consumed by the lamp should include a relative high dc component and components with a frequency of 100 Hz, f_m, $100+f_m$ and $100-f_m$. The corresponding illuminance of a lamp is also expected to include the relatively high dc component and components with a frequency of 100 Hz, f_m, $100+f_m$ and $100-f_m$.

To support this mathematical development, Fourier analysis can be used to analyze the illuminance of the lamp. As an example, the Fourier analysis results of the illuminance of a 230 V, 60 W, glass incandescent lamp under flicker conditions (with m=2% modulation amplitude and f_m=10 Hz modulation frequency) are presented in Table 3-2. As expected, the values of the dc component and components with a frequency of 100 Hz, 10 Hz, 90 Hz and 110 Hz are relatively high. However, the components at frequencies 100+f_m and 100-f_m are not the interesting flicker frequencies because the human eye is not sensitive to such high frequencies. For this reason, the measurement results of interest in this report are the illuminance amplitudes of the modulation frequency component (f_m).

Table 3-2 Fourier Analysis Results of the Illuminance of a 60W Incandescent Lamp under 10Hz (m=2%) Flicker

Frequency (Hz)	DC	10	20	30	40	50	60	70	80	90	100	110
Illuminance (Lux)	1869.3	36.56	0.37	1.78	0.05	3.84	0.05	0.50	0.04	4.07	144.8	3.31

To compare different lamp responses to input voltage fluctuations, the relative illuminance variation is used to evaluate the illuminance variation for the different types of lamps. Using a relative measure is necessary because the average illuminance is not exactly the same for different lamps. This relative illuminance variation can be calculated as shown in (3-3).

$$L_r(f_m) = \frac{L_{f_m}}{L_{av}} \times 100 \tag{3-3}$$

In (3-3), L_r is the relative illuminance variation of the f_m component for different lamp types, L_{fm} is the absolute illuminance of the f_m component, and L_{av} is the average illuminance of this type of lamp. L_{av} is obtained by a luxmeter and is selected as the base value in the calculation.

In order to show the different flicker responses of different lamp types, the per unit value of the relative illuminance variation for different types of lamps is used. As the incandescent lamp is used as the standard lamp in [2], the illuminance variation of the incandescent lamp for different modulation frequencies is selected as base value L_b. $L_{unit}(f_m)$ is the per unit illuminance variation value at frequency f_m relative to the illuminance variation at the same frequency for a 60W incandescent lamp and can be calculated as shown in (3-4).

$$L_{unit}(f_m) = \frac{L_r(f_m)}{L_b(f_m)} \tag{3-4}$$

3.2.2. Measurement Results

The results of two types of measurements are presented in this section. One measurement is used to compare the light intensity variation of different lamp types for the same sinusoidal modulation voltage. Another measurement is used to determine the required sinusoidal modulation voltage amplitude for the different lamp types to produce the same light intensity variation.

3.2.2.1. Standard Sinusoidal Modulation Voltage Amplitude Measurements

In order to determine the flicker responses of different lamp types, measurements were made using the modulation voltage amplitudes shown in Table 3-3. As described in [12], the unit instantaneous flicker level ($P_{\text{inst}} = 1$) should be measured when these modulation amplitudes are applied. For the lamp testing, the lamp output (illuminance) for the different types of lamps were measured for the amplitude/frequency pairs in Table 3-3. The relationships between the relative illuminance variation per unit value $L_{unit}(f_m)$ and the voltage modulation frequency for different types of lamps are presented in Fig. 3-2.

Table 3-3. Flickermeter Input Sinusoidal Voltage Fluctuations
(Input Relative Voltage Fluctuation for One Unit of Perceptibility at Output 5 (see Fig. 3-1))

Voltage Modulation (*m*)		Voltage Modulation (*m*)		Voltage Modulation (*m*)	
Frequency (Hz)	Amplitude (%)	Frequency (Hz)	Amplitude (%)	Frequency (Hz)	Amplitude (%)
0.5	2.340	6.5	0.300	14.0	0.388
1.0	1.432	7.0	0.280	15.0	0.432
1.5	1.080	7.5	0.266	16.0	0.480
2.0	0.882	8.0	0.256	17.0	0.530
2.5	0.754	8.8	0.250	18.0	0.584
3.0	0.654	9.5	0.254	19.0	0.640
3.5	0.568	10.0	0.260	20.0	0.700
4.0	0.500	10.5	0.270	21.0	0.760
4.5	0.446	11.0	0.282	22.0	0.824
5.0	0.398	11.5	0.296	23.0	0.890
5.5	0.360	12.0	0.312	24.0	0.962
6.0	0.328	13.0	0.348	25.0	1.042

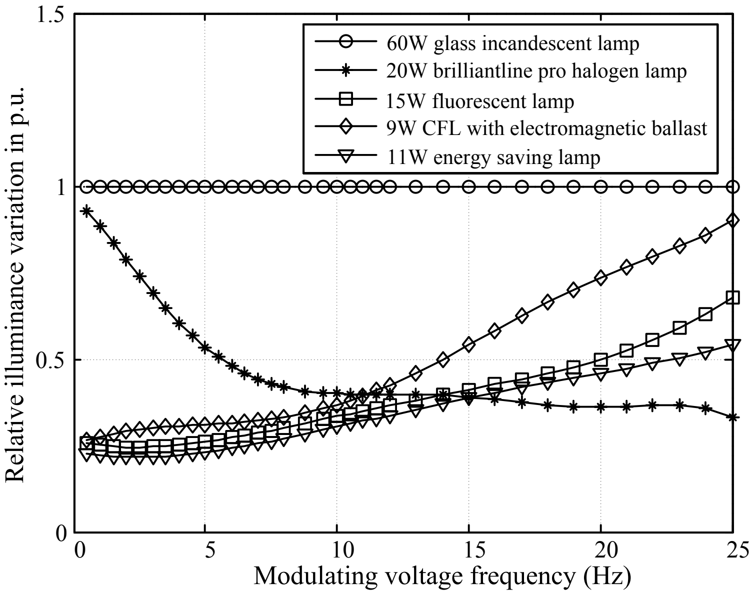


Fig. 3-2. Normalized Flicker Illuminance Responses of Different Types of Lamps Referred to a 60 W Incandescent Lamp (with Modulation Voltage Amplitudes Given in Table 3-3)

As shown in Fig. 3-2, the incandescent lamp is the most sensitive to flicker. The energy saving lamp is the most insensitive to flicker when the voltage modulation frequency is smaller than 15Hz. The halogen lamp becomes the most insensitive to flicker when the voltage modulation frequency varies between 15Hz and 25Hz. This is due to the fact that the tested halogen lamp operates at 12V instead of the 230V supply voltage level. An additional electronic transformer is used for this halogen lamp set. Thus, this electronic transformer influences the flicker response of the halogen lamp. For the energy saving lamp, the specific working principle of the compact fluorescent tube and the additional electronic ballast result in a more stable lamp voltage and current under input voltage fluctuation conditions, i.e. more insensitive to flicker [15] [16].

3.2.2.2. *Instantaneous Flicker Curve (for Sinusoidal Modulation Voltage) Measurements*

As shown in Fig. 3-2, different types of lamps have different light output variations (flicker responses) to the same input voltage fluctuations (flicker voltage). Thus, the flicker sensitivity to the modulation voltage must be different for each lamp type, i.e. the modulation voltage amplitude must be different when the illuminance variation is the same for the different tested lamps. The measurements shown in Fig. 3-3 support this hypothesis.

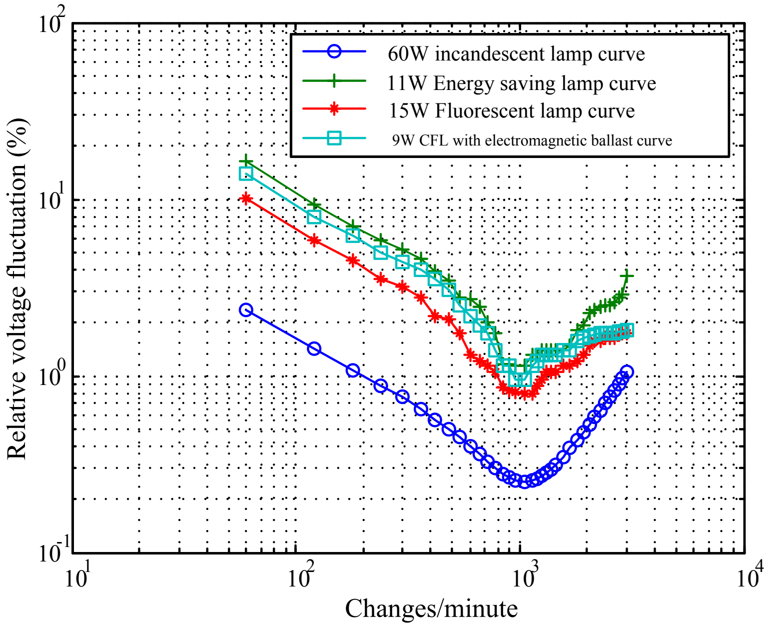


Fig. 3-3. P_{inst}=1 Flicker Curves for Different Types of Lamps With Sinusoidal Modulation

Because a 230V, 60W incandescent lamp is used in several standards, the illuminance variation of a 60W glass incandescent lamp, with the modulation voltage amplitude shown in Table 3-3 (instantaneous flicker level equal to one), is selected as the standard illuminance variation in these tests. The modulation voltage amplitude was measured for different types of lamps for a illuminance variation which has the same value as the standard (60W, 230 V incandescent lamp) illuminance variation. A sinusoidal modulation input voltage is used in this test. The instantaneous flicker curves (sinusoidal modulation voltage amplitude versus voltage modulation frequency when $P_{\text{inst}} = 1$) for different types of lamps are presented in Fig. 3-3.

The conclusion can be drawn that the incandescent lamp is the most sensitive (of the lamps tested) to the sinusoidal modulation input voltage. The energy saving lamp is most insensitive (of the lamps tested) to the sinusoidal modulation voltage.

It is important to recognize that the results presented in this chapter are based on a single set of tests reported in the literature. While the concepts, tests, and measurements are sound, additional tests should be considered to fully validate the measurement results given here. Furthermore, it should be noted that the measurement results for various lamp types should not be generalized across all manufacturers. It is entirely possible that validated test results of multiple lamps of the same type but from different manufacturers could show appreciable variations in overall performance. Additional testing is strongly recommended prior to reaching general conclusions.

4. Flicker Transfer

4.1. Introduction

Another possible reason that high flicker levels, as indicated by high measured P_{st} values, are not necessarily predictive of customer complaints is that measurements are often carried out at HV/EHV locations while locations susceptible to flicker complaints are commonly at LV locations. It is widely recognized that voltage fluctuations are attenuated as they propagate through the supply system. The various causes and effects of this attenuation are generally captured using a so-called "transfer coefficient" that is applied in various flicker calculations. It is important to recognize that this concept of transfer represents a reduction effect (the coefficient is less than or equal to 1.0) that may be due to simple impedance-driven voltage division or more complex phenomena associated with dynamic load response. Because of its (re)active nature, the dynamic load response category of effects is usually termed "attenuation" whereas "transfer" applies to the reduction effect in a more general way. Flicker attenuation should be considered as a subset of the broader concept of flicker transfer.

Existing reports such as [11] and [10] recommend a general flicker transfer coefficient of 0.8 from HV/EHV locations to MV. This 0.8 factor means that roughly 80% of the flicker at an upstream (HV/EHV) location will appear at some downstream (MV) location. The 20% reduction will be due to the effects of the network and the downstream loads. If this attenuation is not accurately included in the development of an EMC strategy for flicker, it is indeed likely that resultant planning levels and emission limits will be excessively conservative. This conservatism could translate into a poor correlation between measured HV/EHV flicker levels and LV user flicker complaints.

It is possible to consider the attenuation phenomenon through analytical, laboratory, and field measurement experiments. Each of these approaches is considered in this chapter with supporting details provided in Annex B [10][17][18]. Field measurements and experimental research have revealed that loads with certain characteristics assist in attenuating flicker as it propagates from its source to lower voltage levels that supply flicker-sensitive loads. Most importantly, the induction motor has been shown to behave as a dynamic load that helps to smooth voltage fluctuations and subsequently reduce flicker. As a general guideline, some empirical flicker transfer ratios are given in [10] for transfer of flicker between different voltage levels.

Considering the basic scenario in Fig. 4-1, it is straightforward to consider the flicker attenuation phenomenon. For a flicker source in the HV grid that produces some measurable P_{st} value, the corresponding flicker level measured in a local MV area will likely be less than that present in the HV supply. This attenuation is largely due to the load response to the voltage fluctuations. It is certain that the load power is not constant under the conditions of fluctuating voltages, but the manner in which the load changes dynamically remains the subject of research. Variable PQ load models with voltage sensitivity, variable load impedances, and complete time domain simulations can all be used to capture the attenuation phenomenon. Which method is best may well depend on the available data and, when insufficient data is available, the attenuation effect can always be measured [24].

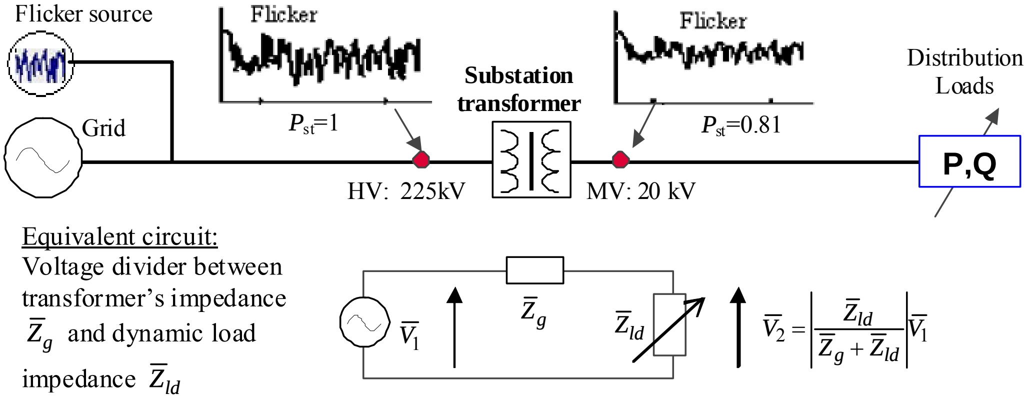


Fig. 4-1. Flicker Propagation From HV to MV Network

4.2. Laboratory Test Results and Theoretical Work

The results from recent experimental and theoretical research [19]-[23] indicate that directly-connected induction motors help attenuate modulating frequency components that are present in the supply voltage thus leading to attenuation of the overall flicker. A low power laboratory experimental platform consisting of a sinusoidally amplitude modulated voltage source connected to an induction motor through a simple impedance was used to demonstrate the flicker transfer [19]. A switchable passive load that is equivalent to the steady state operating impedance of the induction motor was also used at the downstream load location for comparison purposes. Analysis showed different levels of attenuation with regard to the two side bands of the sinusoidally amplitude modulated voltage waveform when the induction motor was connected at the downstream load location. Very little or no attenuation was observed when the passive load was connected instead of the induction motor. The noticeable aspect through the experimental work was the dependency of the attenuation of voltage fluctuations on the modulating frequency when the induction motor load was connected. The overall flicker attenuation and its dependency on the modulating frequency are clearly demonstrated in Fig. 4-2 for the motor load in comparison to that exhibited by the passive load. Considering the fact that realistic voltage fluctuations contain different frequency components, flicker transfer coefficients are hence seen to depend on the operating parameters of the fluctuating source which lead to flicker in addition to system impedances (which connect the fluctuating source to the load). The dominant role that induction motor loading, as a percentage of total load, can play in flicker attenuation is shown in Fig. 4-3. The combined effects of both modulation frequency and motor load percentage are shown in Fig. 4-4. In Figs. 4-2 through 4-4, the notation T_{PstAB} is used to denote the flicker transfer coefficient from some upstream source (point A) to some downstream location (point B). The results in Fig. 4-2 were obtained via experimentation with a 2.2 kW motor driving a load with a linear torque-speed relationship. The results in Figs. 4-3 and 4-4 are based on simulations of a 1.68 MW motor driving a load where torque is proportional to speed squared.

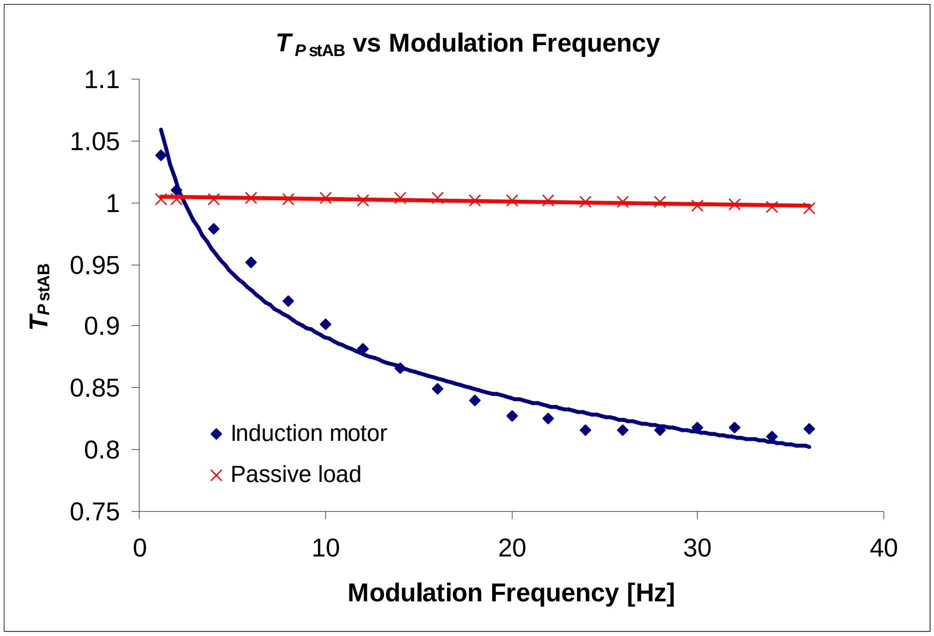


Fig. 4-2. Variation of Flicker Transfer Coefficient with Modulating Frequency [19]

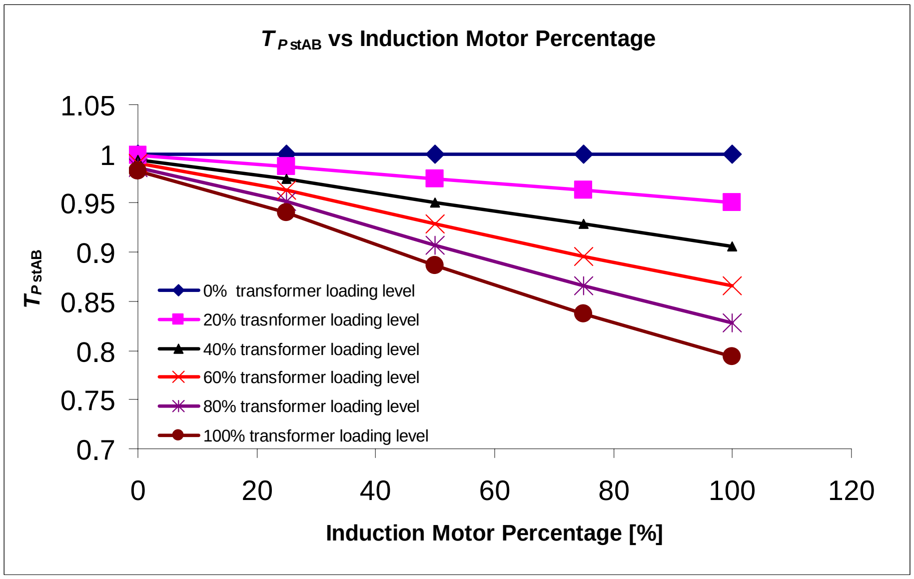


Fig. 4-3. Variation of the Flicker Transfer Coefficient with Proportion of Induction Motor Load at the Downstream Location and Total Transformer Loading Level [23]

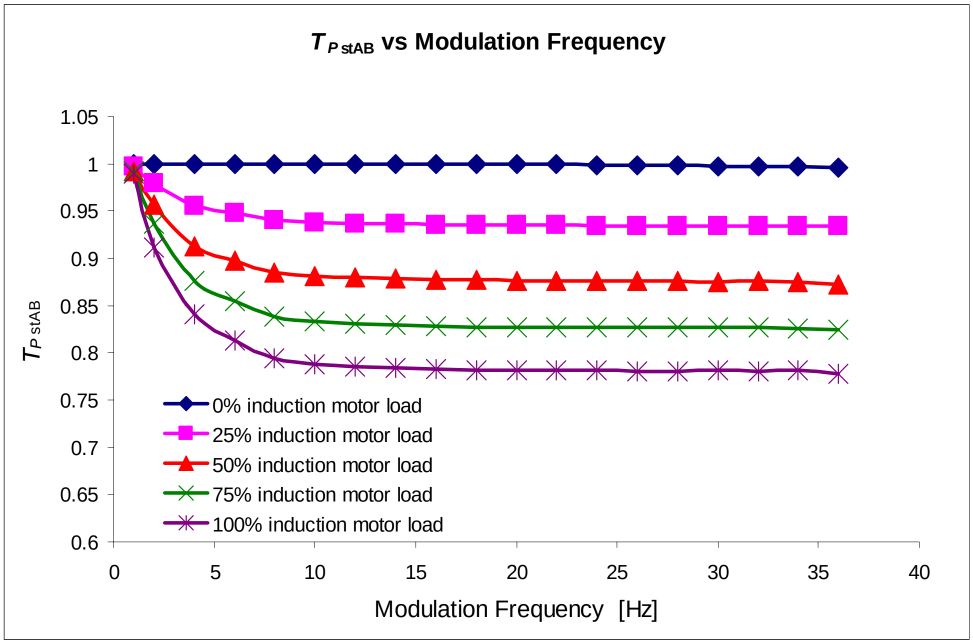


Fig. 4-4. Variation of the Flicker Transfer Coefficient with Modulating Frequency and the Proportion of Induction Motor Loading at the Downstream Location [23]

Preliminary time domain simulation work on a radial network clearly demonstrates (Figs. 4-3 and 4-4) that the flicker transfer coefficient not only depends on the modulation frequency but also on the percentage of induction motors in the total load at a busbar and the loading level on the transformer through which the downstream load busbar is supplied.

Given the fact that motor load clearly acts to smooth out voltage fluctuations and attenuate flicker, it is appropriate to consider the effect of the size of the motors on the overall phenomena. Smaller motors will have lower stored energy, both mechanical and electromagnetic, with which to compensate supply voltage fluctuations. It is to be expected therefore that larger motors will more effectively attenuate flicker. Results of analytical evaluations (single motor supplied by an ideal source with fixed source reactance X_s specified as a percentage of motor size) of the effect of motor size on attenuation are shown in Fig. 4-5. It is clear that larger motors are indeed more effective in attenuating flicker at lower modulation frequencies whereas attenuation effects are essentially independent of motor size for higher modulation frequencies. For each motor in Fig. 4-5, the mechanical load torque is assumed proportional to speed squared.

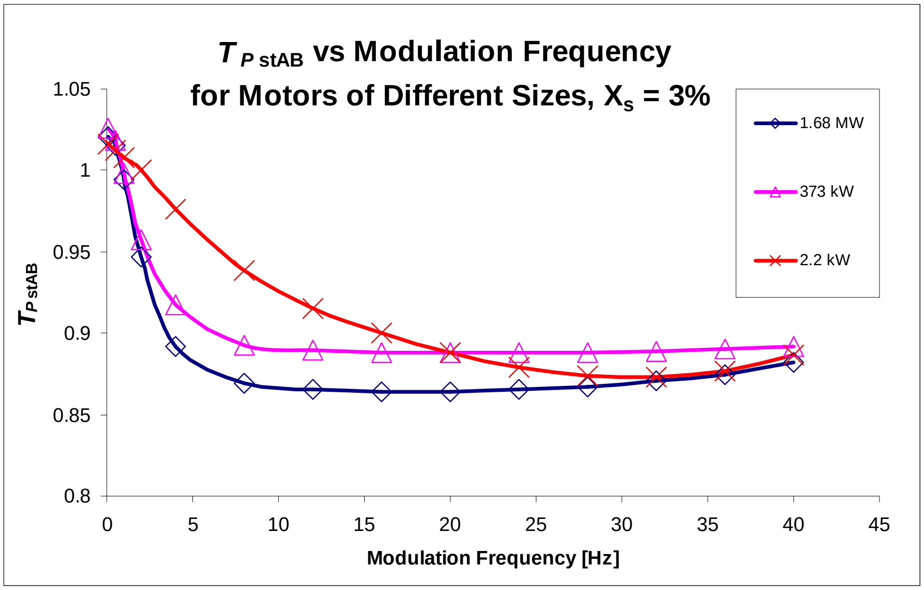


Fig. 4-5. Effect of Motor Size on Flicker Attenuation

Noting the fact that mains-connected induction motors help attenuate flicker, extensive theoretical research has been undertaken to examine the mechanism describing the behavior of induction motors when they are subjected to regular voltage fluctuations that arise due to sinusoidal modulation [19][23]. The subsequent results clearly indicate that an induction motor tends to respond to voltage fluctuation in such a manner that its effective impedance is much smaller than the steady state impedance. Further, this effective impedance has been shown to depend on the modulating frequency. This work has been extended to examine the flicker transfer and attenuation in radial power networks [21] clearly demonstrating the flicker attenuation associated with induction motors. The flicker attenuation behavior, as expected, has been shown to depend on the series network impedance between the fluctuating source and the load. Additional theoretical studies in relation to interconnected networks also indicate a similar behavior [22]. Significant additional theoretical discussion of these points is given in Annex B.

4.3. Modeling of Downstream Flicker Propagation

When detailed analysis involving complex motor models is not appropriate, other means for evaluating flicker attenuation should be considered. The typical calculations for flicker studies are carried out in the frequency domain using phasors and impedances to determine voltage fluctuations for particular load variations [24] [25]. As was clearly demonstrated in the previous section, assuming static characteristics for non-fluctuating loads could lead to significant errors in accuracy regarding flicker attenuation. While motor loads are well documented in the literature and in this report with regard to their attenuating benefits, most loads contribute at least some beneficial flicker attenuation characteristics based on their voltage dependence. One effective way to capture these dependencies is to use assumption sets that are common in bulk power system voltage dynamic studies where sensitivities of real and reactive demand with respect to voltage are commonly included.

For a given substation (Fig. 4-1), when the power supply voltage fluctuates, a distribution load can behave very differently depending on its composition; the variations of the active power ***P*** and reactive power ***Q*** of the load may be more important than the grid voltage variations. In general, when voltage goes down, the overall distribution system load impedance increases (or powers go down) and the relative voltage drop across the substation transformer consequently decreases. This reduced voltage drop on the substation transformer owing to load impedance change can be seen easily with the equations embedded in Fig. 4-1. This is the observed flicker attenuation phenomenon. Flicker is mainly caused by variation of ***Q*** because the network impedance is generally inductive. A significant $\Delta Q/\Delta V$ sensitivity may contribute a considerable flicker attenuation effect. Studies [26] show that a great number of loads have high $\Delta Q/\Delta V$, i.e., a small voltage fluctuation can cause an important variation of reactive power, which brings about the flicker attenuation effect. In Table 4-1 are shown some typical real and reactive demand sensitivities for various load sectors. If other data is available regarding sensitivities in specific locations, perhaps extracted from field test measurement results, it may be preferable to the more generic data given here.

Table 4-1: Typical Power Variations Versus Voltage Fluctuation

Load Sector	ΔP/ΔV (per unit)	ΔQ/ΔV (per unit)
Industrial	0.18	6.0
Commercial	1.3	3.1
Residential	1.5	3.2

As mentioned previously, the induction motor helps attenuate modulating frequency components that are present in the supply voltage subsequently leading to an attenuation of the overall flicker. Moreover, power-regulated distribution system loads such as adjustable speed drives may also play a role in flicker attenuation from HV to MV.

While there is no dedicated load model to simulate flicker propagation, recent research has been focused on developing a simplified distribution system load model based on $\Delta P/\Delta V$, $\Delta Q/\Delta V$, and a first order high-pass filter to capture a load time response characteristic. Considering reactive power demand only, the model is of the form shown in (4-1).

$$\Delta Q = \mathrm{K_v}\left(\frac{s\tau}{1+s\tau}\right)\Delta V \tag{4-1}$$

A similar model, with different coefficients, would be used for real power demand. In these models, a voltage variation *ΔV* is calculated using a specific (quasi-steady state r.m.s.) voltage V and a mean value voltage V_m. Afterwards, power variations ΔP and ΔQ are determined from ΔV using the coefficients K_v (see Table 4-1 where K_v is taken as the applicable $\Delta P/\Delta V$ or $\Delta Q/\Delta V$ constant for the load type being considered). The load power changes are not allowed to occur in a step-change manner; they are sent through a high-pass filter G(s) in order to take into account the duration of voltage variation (load response time) as shown in Fig. 4-6. Typical time constants for the load response are on the order of 0.1-1.0 seconds with 0.3 seconds being recommended for general use. The output of this time delay block is taken as the actual change in load power (both real and reactive). The obtained power variations ΔQ and ΔP are used to modify the load equivalent impedance model over the period of time of interest in the flicker study. Other than the time delay component of the load model, all the calculations are carried out in the frequency domain. This type of approach, therefore, is a hybrid flicker analysis method involving both the time and frequency domains. A case study showing the effectiveness of this method is presented in Annex B.

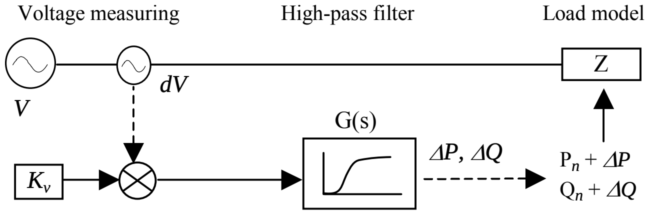


Fig. 4-6. Principle of Flicker Behavior Modeling of Distribution Load

4.3.1. Simplified Method to Include Flicker Transfer

Site measurements and theoretical analysis repeatedly show that the general flicker disturbance is attenuated when crossing HV/MV substations. The principle of this attenuation is due to the dynamic impedance of distribution load such as is commonly found in induction motors, adjustable speed drives, power regulation units, etc. As previously discussed, the precise flicker transfer coefficient from HV to MV depends on many factors including the

- Type of distribution loads;
- Composition of load types (industrial, commercial, residential);
- Time constant(s) of load response(s) (power regulation time constant for instance); and
- Upstream impedance (transformer and grid).

For an actual case, it is very difficult to get sufficiently detailed and accurate information on all of these factors. In order to simplify the flicker propagation assessment from primary (HV) to secondary (MV) of a substation transformer supplying general industrial and commercial load, a simplified approach is to assume a linear relationship between load level and attenuation based on a recommended transfer coefficient (e.g., T_{Pst}=0.8 HV→MV as suggested in [11]). This simplified approach shown in (4-2) captures the fact that attenuation depends on loading level as described previously but does not cover frequency dependence. As shown in Fig. 4-7 (and supported by Fig 4-3), attenuation is zero for no load and maximum for full load.

$$T_{P\mathrm{stHM}} = \frac{P_{\mathrm{stMV}}}{P_{\mathrm{stHV}}} = 1 - \left(\left(1 - T_{P\mathrm{stHM,assumed}}\right) \frac{\text{Transformer Loading}\,(\%)}{100} \right) \tag{4-2}$$

The following definitions apply to (4-2):

P_{stMV}: Flicker severity on the secondary of the substation transformer,
P_{stHV}: Flicker severity on the primary of the substation transformer,
Transformer Loading (%): Transformer loading from 0% to 100%, and
$T_{P\mathrm{stHM,assumed}}$: Assumed transfer factor such as 0.8 for HV→MV.

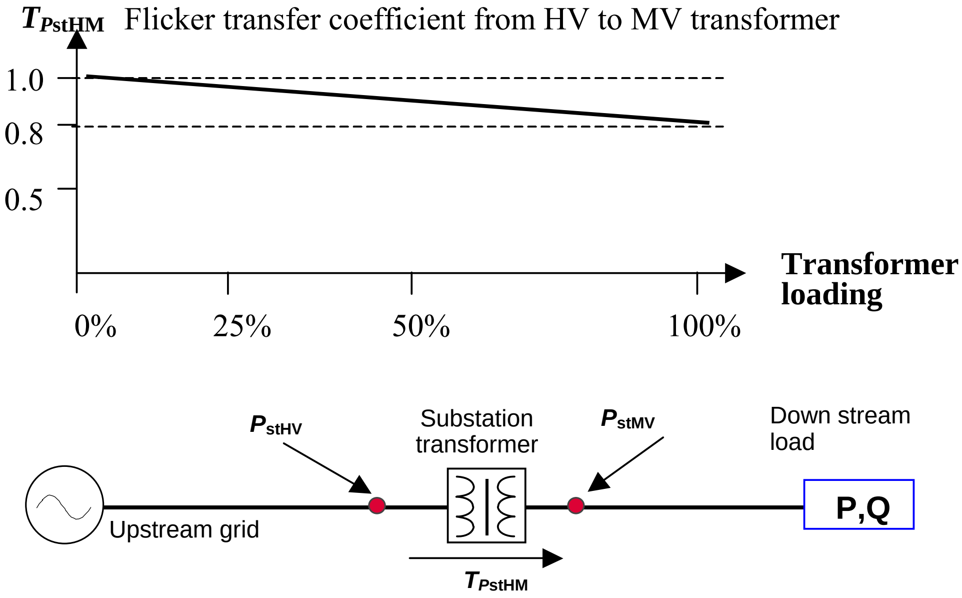


Fig. 4-7. Flicker Transfer Coefficient From Primary to Secondary of Substation Transformer

4.4. Measurement of Flicker Transfer

In some cases, it is possible to directly measure flicker transfer/attenuation using synchronized instrumentation. Depending on the instrumentation available, it is possible to measure the total transfer effects from a fluctuating source in the HV/EHV network to the potentially sensitive user locations in the MV/LV network. This total transfer measurement would include both network effects and the attenuation effects of MV/LV load as discussed in previous sections.

As an example, the sample network diagram shown in Fig. 4-8 includes the location of an

HV/EHV fluctuating load (in this case an electric arc furnace (EAF) in substation A) and the flicker measurement locations used to determine the total transfer factor from this location to the shown MV location in substation B.

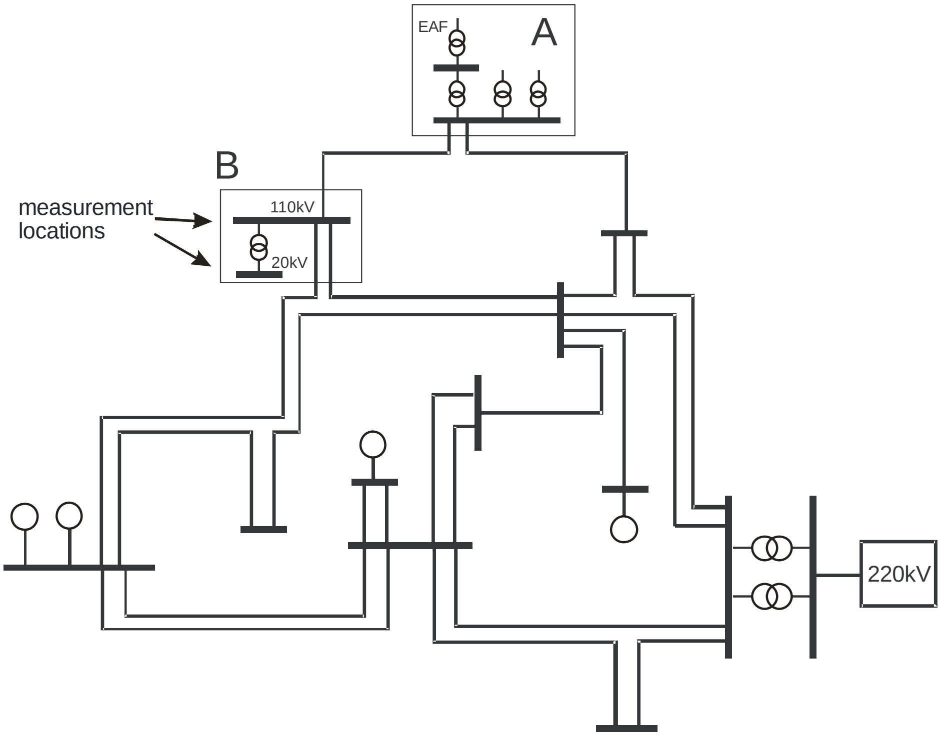


Fig. 4-8. Network Diagram for Illustration of Transfer/Attenuation Measurement

In this sample case, measurements of flicker levels at the HV bus in station B are plotted against flicker levels at the MV bus in station B as shown in Fig. 4-9. For the data shown, the EAF in station A is in operation and dominates the response.

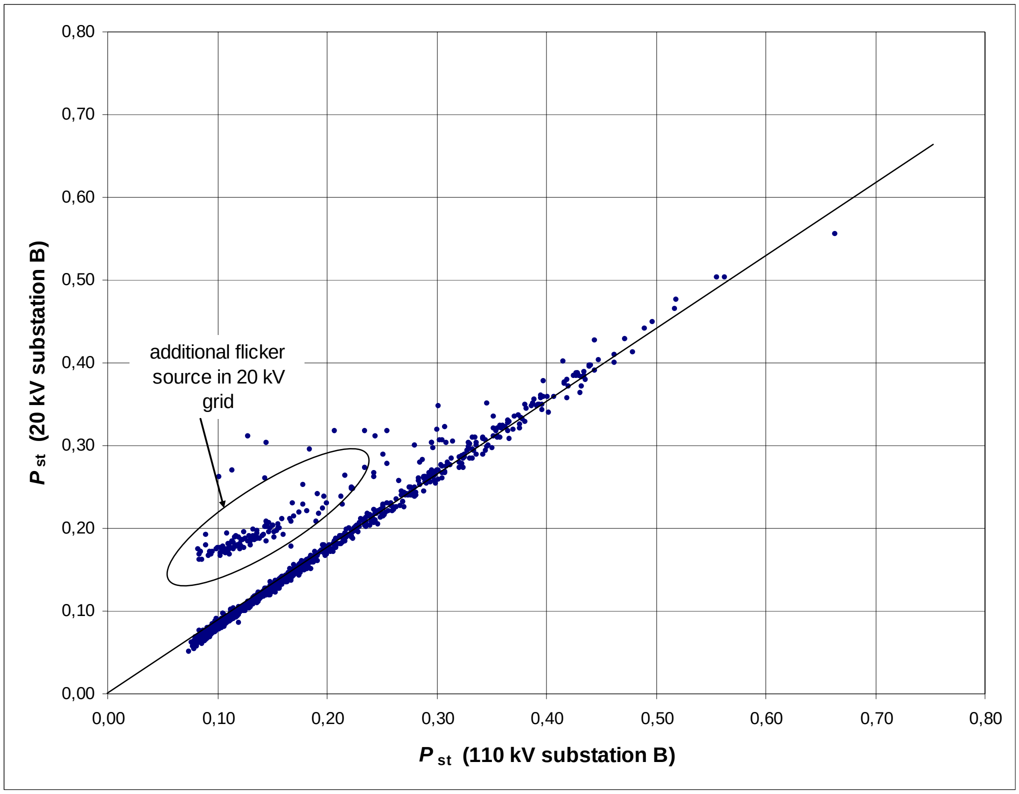


Fig. 4-9. Measured Attenuation Between HV and MV locations

In this case, the clearly linear relationship between the two measurement sets gives a transfer factor HV/EHV→MV of about 0.87 (the slope of the best-fit line). Note that care is required to determine the cause of any poorly-correlated points such as those identified in Fig. 4-6 as being associated with other MV fluctuating loads in station B. It is clear from these types of measurements that attenuation does indeed occur between voltage levels, and the main cause of this beneficial attenuation is most likely the load response in the MV/LV network.

In cases where the data exhibit greater spread than shown in Fig. 4-9, it is preferable to use a line through the lower portion of the data, perhaps through the actual lower boundary. Such a line would have a smaller slope and thus would provide a more conservative value for the transfer factor. This type of approach is especially recommended when significant dispersion exists and several flicker sources are known to exist and operate in the lower voltage portion of the network being monitored.

Note that measurement of transfer factors is dependent on the indices used. The method of Fig. 4-9 relies essentially on curve-fitting techniques applied to a number of simultaneously recorded P_{st} values. Other methods of direct measurement may utilize a ratio of 95th (or even 99th) percentile P_{st} or P_{lt} values determined over some suitable period. In some cases, appreciably lower values for transfer factors may be obtained due to the smoothing effects of the statistical evaluations.

5. Rapid Voltage Changes

5.1. Introduction

The visual discomfort due to light flicker is the most frequent reason to limit the voltage changes induced by fluctuating installations connected to power systems. On the other hand, system operators or owners have to maintain the voltage magnitude within narrow limits and individual installations should not produce significant voltage variations, even if they are tolerable from the flicker point of view. According to IEC TR 61000-3-7 [11], "Rapid voltage changes, even within the normal operational voltage tolerances, are considered as a disturbing phenomenon."

Beside the fact that they can cause or contribute to light flicker when their repetition rate is high enough, other possible effects and consequences of rapid voltage changes are sometimes reported in the literature: they can cause the malfunction of some control systems acting on the voltage angle; they can induce annoying braking or accelerating torques on electrical motors; and they could result in the impairment of some very sensitive electronic equipment.

With the growing penetration of dispersed generation units in the LV distribution networks, the number of voltage fluctuations is likely to increase. These phenomena take the shape of rapid changes due the varying character of the primary energy (photovoltaic, wind etc.) and can mostly result in small temporary overvoltages, the effect of which is still not well documented.

At this time, there is a lack of information to assert definitely that rapid voltage changes constitute a real EMC problem. When their repetition rate is very low, the only practical observation is that they induce some psychological discomfort to the power grids users, giving them the feeling that "something wrong or bad is happening on the grid." This rather subjective feeling leads sometimes to complaints (although not being flicker, in the sense of IEC 61000-4-15 [12]) with which utilities have to cope. One recent study has associated rapid voltage changes with objectionable light flicker in an attempt to better quantify limiting values for the phenomenon [27].

5.2. Concept and Definition

Rapid voltage changes are usually defined as changes in fundamental frequency r.m.s. voltages over several cycles. This concept is illustrated Fig. 5-1. Rapid voltage changes are usually quick transitions in r.m.s. voltage between two steady-state conditions where steady-state is considered to be a period lasting one second (or more). They could also be in the form of cyclic or repetitive changes. They are usually expressed as a percentage of the nominal or declared voltage, as shown in Fig. 5-2. Note that these figures (5-1 and 5-2) show a voltage decrease, but the concept is broader and also applicable to an increase.

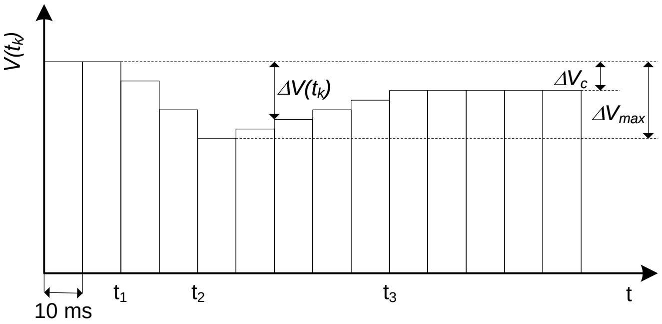


Fig. 5-1. The Concept of Rapid Voltage Change ([28][29])

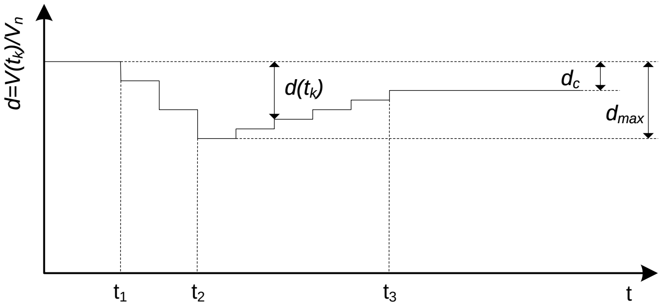


Fig. 5-2. The Concept of (Normalized) Rapid Voltage Change ([28][29])

According to the representation in Fig. 5-2, the following parameters are defined:

- d_{max}: the minimal (or maximal) value of the voltage change reached during the transient period of the change and
- d_c: the "steady-state" value of the voltage change reached after the transient period.

In most cases, limits on rapid voltage changes are specified in terms of these two parameters.

5.3. Causes and Origin

Rapid voltage changes are mostly caused by switching operations such as:

- Motor starting;
- Capacitor bank or shunt reactor switching on and off;
- Load switching on and off; and
- Transformer tap-changer operations.

They can also be induced by sudden load variations as well as by power output variations from distributed energy resources such as solar or wind.

5.4. Consequences

The major known effects and consequences of rapid voltage changes include:

- They can cause or contribute to light flicker;
- They can cause the malfunctioning of some control systems acting on the voltage angle;
- They induce braking or accelerating torques on electrical motors; and
- They can result in the impairment of some very sensitive electronic equipment (rather rare).

5.5. Applicable EMC Standards

5.5.1. Compatibility Levels in LV and MV

The EMC international standards describing the electromagnetic environment in LV and MV (IEC 61000-2-2 [31] and 61000-2-12 [32], respectively) both state that "In normal circumstances, the value of rapid voltage changes is limited to 3% of nominal supply voltage. However step voltage changes exceeding 3% can occur infrequently on the public supply network. Furthermore, following exceptional load changes or switching operations, voltage excursions outside the normal operational tolerances (for example ±10 % of the declared supply voltage) are possible for a few tens of seconds until on-load tap-changers on the high voltage-medium voltage transformers have operated."

5.5.2. Planning Levels and Emission Limits in MV, HV and EHV

Planning levels are disturbance levels that can be used for the purpose of determining emission limits, taking into consideration all installations which may cause rapid voltage changes. Planning levels are specified by the system operator or owner for all system voltage levels and can be considered as internal quality objectives of the system operator or owner and may be made available to individual customers on request. Only indicative values may be given because planning levels will differ from case to case, depending on system structure and circumstances.

In [11], planning levels for MV are suggested based on the compatibility level. For HV-EHV, no established compatibility levels exist and suggested levels are provided based on:

- existing HV-EHV practices regarding rapid voltage changes and
- the need to provide margin between MV and HV-EHV for the purposes for overall EMC coordination.

In Table 5-1 are given indicative planning levels for rapid voltage changes $\Delta V/V_N$ (d_{max} in Fig. 5-2) for infrequent events (expressed in per cent of the nominal voltage). These limits depend on the number of such changes in a given time period. Note that less frequent voltage changes are not covered in [11]. However, they may be of importance on some systems.

Table 5-1. Indicative Planning Levels for Rapid Voltage Changes as a Function of the Number of Such Changes in a Given Period ([11])

Number of changes N	$\Delta V/V_N$ (%)	
	MV	HV / EHV
$n \leq 4$ per day	5 – 6	3 - 5
$n \leq 2$ per hour and > 4 per day	4	3
$2 < n \leq 10$ per hour	3	2.5

According to this table, the permissible voltage change $\Delta V/V_N$ (%) and number of changes in a given period should be applied so that the number of changes of magnitude $\Delta V/V_N$ does not exceed the number specified within the total time period corresponding to the rate (e.g. no more than 4 changes of 6 % are permitted at MV during any one 24 hour period). Higher values may be permissible under abnormal system conditions.

The coordination approach recommended in [11] relies on individual emission limits being derived from the planning levels so that overall EMC is maintained. Because the indicative planning levels are defined in terms of numbers of occurrences of a specific rapid voltage change level permitted during a specific interval, emission limits for individual installations shall be defined by the system operator or owner on a case by case basis taking into account the particular operation and impact of each installation that may cause rapid voltage changes in the system of interest. The combined effect of all installations should not result in rapid voltage changes exceeding the planning levels set by the system operator or owner.

5.5.3. Emission Limits for LV Appliances

The voltage changes produced by individual pieces of equipment intended to be connected to LV public grids are limited by EMC standards. The relevant international standards dealing with limits for rapid voltage changes due to LV equipment are

- IEC 61000-3-3 (equipment with rated current ≤ 16 A and not subject to conditional connection) [28];
- IEC 61000-3-11 (equipment with rated current ≤ 75 A and subject to conditional connection) [29]; and
- IEC 61000-3-5 TR (equipment with rated current > 75 A) [30].

The limits stipulated in [28] are related to the complex LV reference impedance Z_{ref} which is actually a specification of separate equivalent impedance values for both phase and neutral conductors as shown in Fig. 5-3.

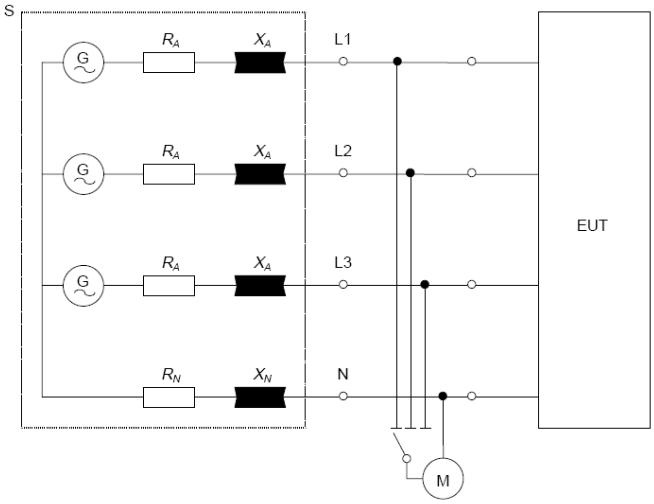


Fig. 5-3. Reference Network for Voltage Changes Testing, Applicable to LV Appliances with Rated Current ≤ 16 A (reproduced from [28])

Referring to Fig. 5-3, the complex reference impedance Z_{ref} is defined by:

$R_A = 0.24\ \Omega$ and $X_A = 0.15\ \Omega$ at 50 Hz and
$R_N = 0.16\ \Omega$ and $X_N = 0.10\ \Omega$ at 50 Hz.

The value of this impedance has been chosen on a statistical basis following an international enquiry. It is intended to give an upper boundary of the impedance for 90% of the 230 V, 50 Hz LV connection points all over the world (future revisions of the relevant documents are expected to include values for other systems). Considering this reference network, limits are given for d_{max} and d_c (see Fig. 5-2) under specific test conditions described precisely by the standard for most common LV equipment.

According to [29], the same limits apply for LV equipment with rated current greater than 16 A (and up to 75 A), but with a complex test impedance Z_{test} possibly smaller than the reference impedance. The value of this test impedance must be declared by the manufacturer of the equipment and it is up to the user to verify with the local distribution system operator or owner that the impedance at the point of connection is actually lower than or equal to the declared test impedance.

5.5.4. Emission Limits for Large LV Installations

Beside standards regarding individual LV pieces of equipment, the future technical report IEC 61000-3-14 is intended to apply to large LV installations exceeding a minimum size. This minimum size (S_{min}) is to be specified by the system operator or owner depending on the system characteristics. The coordination approach recommended in IEC 61000-3-14 will be similar to that recommended in IEC 61000-3-7. It relies on individual emission limits being derived from the planning levels so that overall EMC is maintained. Because the indicative planning levels are defined in terms of numbers of occurrences of a specific rapid voltage change level permitted during a specific interval, emission limits for large

LV installations shall be defined by the system operator or owner on a case by case basis taking into account the particular operation and impact of each installation that may cause rapid voltage changes in the system of interest. The combined effect of all installations should not result in rapid voltage changes exceeding the planning levels (LV) set by the system operator or owner.

5.6. Assessment Procedures

5.6.1. Measurement Method

No standardized measurement method exists for rapid voltage changes. It is recommended in IEC 61000-3-7 that the assessment procedure be based on measured changes in r.m.s. voltage considering only the power frequency component with transients removed. In practice, the shortest possible multi-cycle window should be used to avoid artificially smoothing the desired r.m.s. fundamental frequency voltage change. More specifically, single-cycle r.m.s. values measured according to [34] are normally used.

5.6.2. Emission Level Assessment

Rapid voltage change emission levels can be assessed analytically based on the equivalent circuit and vector diagram of Fig. 5-4 where all quantities are complex values [11].

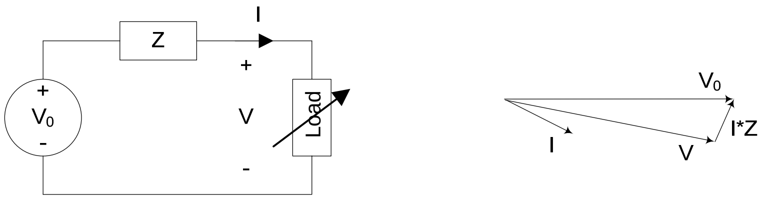


Fig. 5-4. Equivalent circuit and vector diagram for emission assessment

By measuring the cycle-by-cycle active (ΔP) and reactive (ΔQ) power variations for a particular load, the resulting voltage changes can be directly estimated from (5-1).

$$\frac{\Delta V}{V_0} = \frac{R\Delta P + X\Delta Q}{V_0^2} \tag{5-1}$$

In (5-1), R and X are the resistive and reactive parts, respectively, of the reference (or test) impedance for the assessment (contractual impedance).

5.6.3. Indices for Rapid Voltage Changes

Reference [33] proposes the definition of indices for the characterization of rapid voltage changes that are computed considering the standard measured values of the r.m.s. voltage according to IEC 61000-4-30 [34]. In this standard, r.m.s. values of the voltage calculated over 150 (180)-cycle (i.e. ± 3 seconds) are defined as "very-short" values. Values obtained from a calculation over a 10-minute period of time are called "short" values. In the proposed indices, however, the window over which the value is calculated is a sliding rather than a stepping window.

Using each 150 (180)-cycle interval, a 10-minute ("short") value at time t_k can be defined resulting from a calculation over the preceding 10 minutes worth of three-second values, obtained at times t_i, as shown in (5-2).

$$V_{sh}(t_k) = \sqrt{\tfrac{1}{200} \sum_{i=k-200+1}^{k} V_{vs}{}^2(t_i)} \tag{5-2}$$

In order to characterize the voltage variations, a "3-second very-short variation value" can be defined as the difference between the "short" and the "very-short" values evaluated at each three-second interval (i.e. the difference between the three-second r.m.s. voltage and the r.m.s. value of all three-second values over the preceding 10 minutes) as shown in (5-3).

$$\Delta V_{vs}(t_k) = V_{vs}(t_k) - V_{sh}(t_k) \tag{5-3}$$

This can be interpreted as a high-pass residue of the very-short values after taking the 10-minute averages. From the three-second very-short variation values, a "10-minute very-short variation value" can be calculated for every 10-minute time stamp [34] as shown in (5-4).

$$\Delta V_{sh}(t_j) = \sqrt{\tfrac{1}{200} \sum_{i=j-200+1}^{j} \Delta V_{vs}{}^2(t_i)} \tag{5-4}$$

In (5-4), t_j is a time point corresponding to a 10-minute time stamp.

A voltage measurement could then be reduced to three values over every 10-minute interval:

- The short-time (10-minute) r.m.s. voltage (5-2);
- The 10-minute very-short variation, characterizing rapid voltage changes over that interval (5-4); and
- The short-time flicker severity P_{st}.

In Figs. 5-5 through 5-8 are shown examples of voltage measurements (LV) and the corresponding rapid voltage change indices as defined previously.

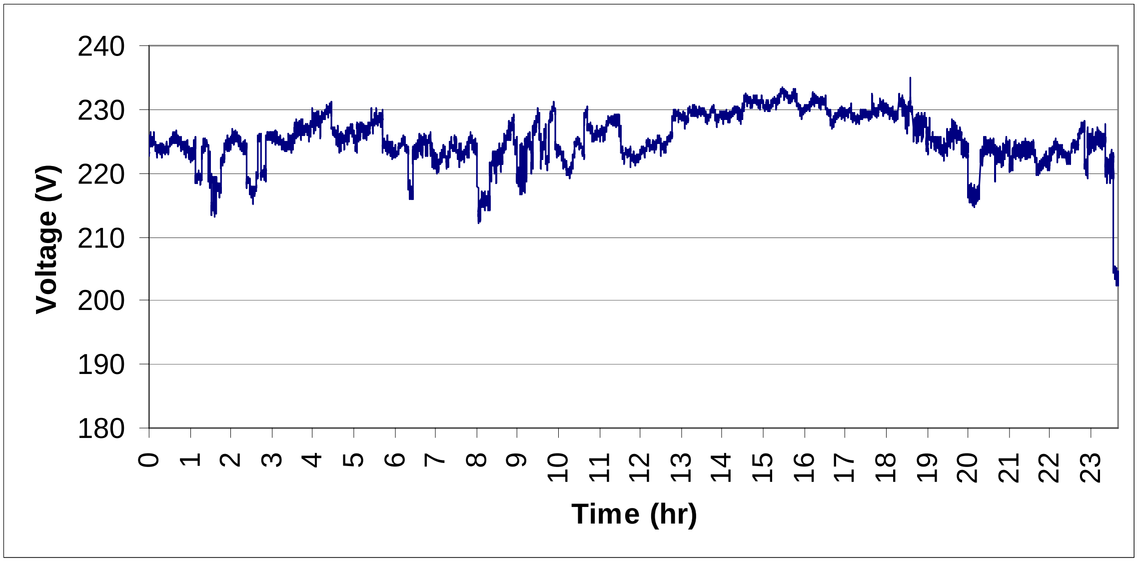


Fig. 5-5. Very Short (3 s) r.m.s. Voltage

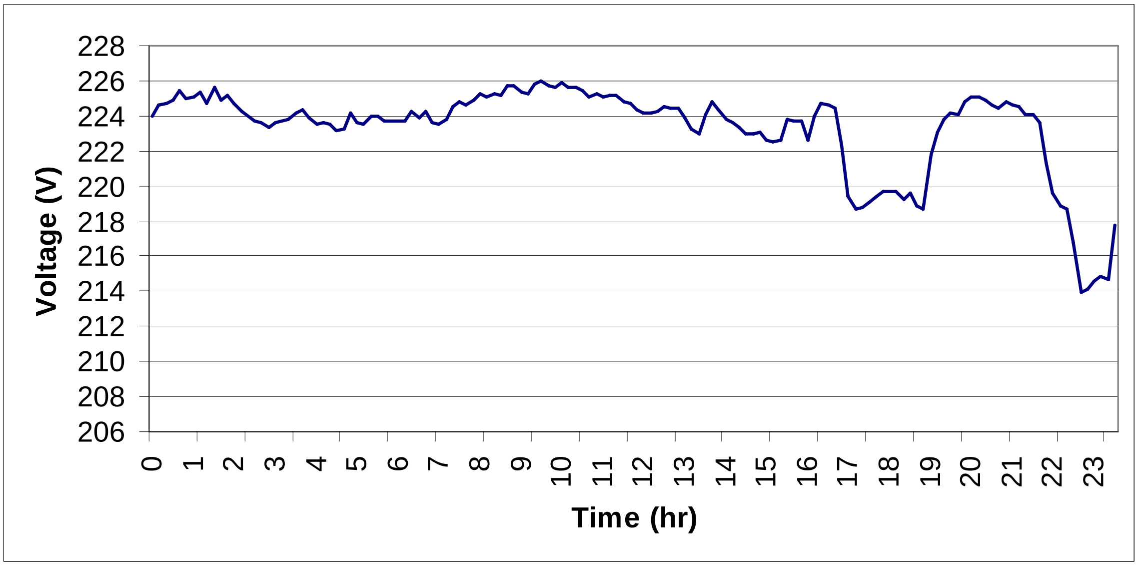


Fig. 5-6. Short (10 min) r.m.s. Voltage

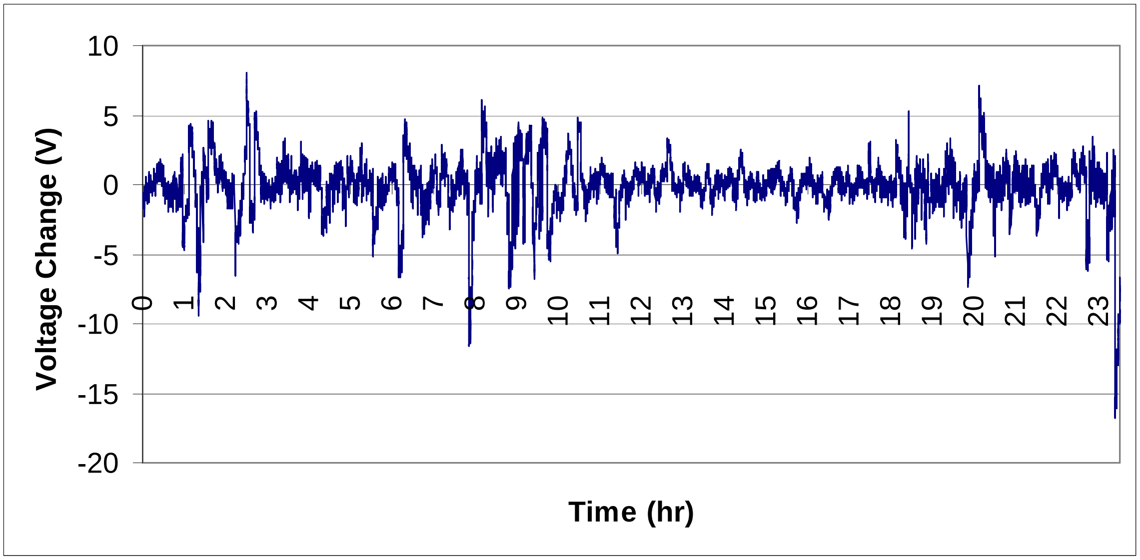


Fig. 5-7. Very Short r.m.s. Voltage Variation

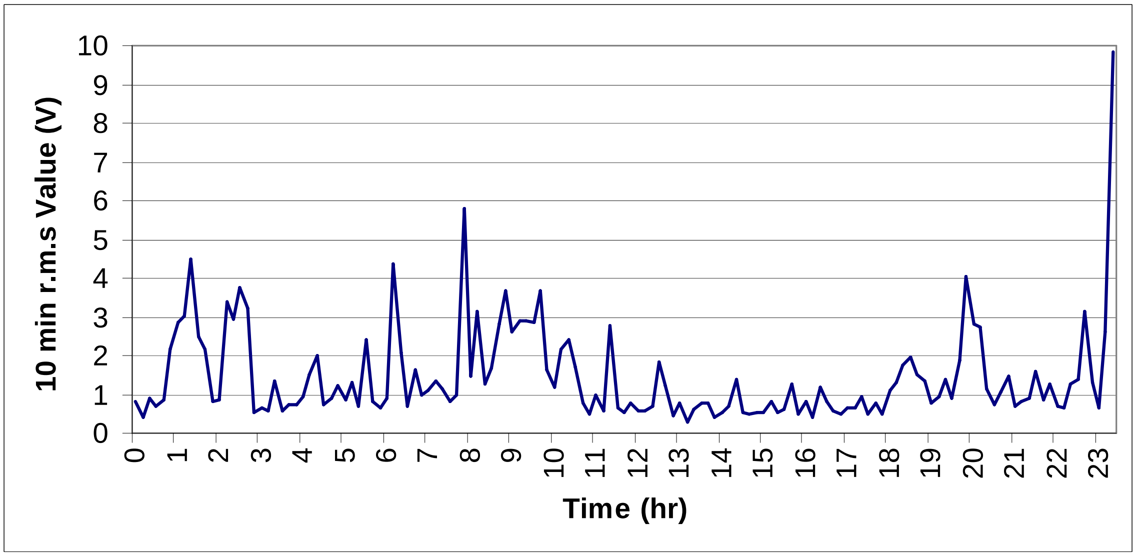


Fig. 5-8. Very Short Voltage Variation 10 min r.m.s. Values

Note the somewhat random very-short variation voltage shown in Fig. 5-7. No apparent trends exist although the variations are clearly both above and below the 10 min values at different points throughout the recorded day.

The aim of the very-short variation indices is to provide additional information to quantify voltage variations. If these indices were strongly correlated with existing indices, there would be no need for the proposed additional ones. The classical flicker indices also quantify short-duration fluctuations in voltage amplitude. Therefore a comparison was made between the 10-minute very-short variation and the short-term flicker severity at one site. The results are shown in Fig. 5-9 and indicate that these two indices are non-correlated. This of course does not rule out that there is no correlation for any other site, but it does show that there is no general correlation between the flicker indices and the very-short variation indices. This lack of correlation suggests that information is present in one index which is not present in the other. Note that the results in [33] indicate similar poor correlation between P_{st} and very short voltage variation.

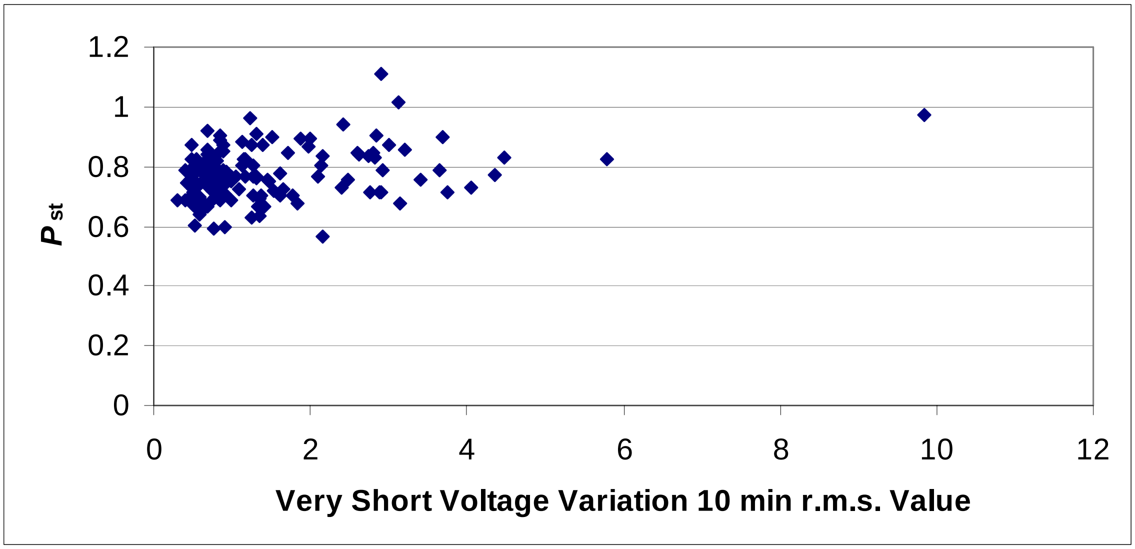


Fig. 5-9. Correlation Between 10 min Very Short Variation and Short Term Flicker Severity

Based on the "10-minute very short variation" index as proposed, it is also possible to define a "three-second half-cycle variation" index. This three-second half-cycle variation index could be useful to manage rapid voltage changes produced by events such as load energizations (e.g., motor starting) and network switching actions (e.g., capacitor switching). The necessary equations are shown in (5-5) and (5-6) where V_{hp} represents the half-cycle r.m.s. value.

$$\Delta V_{hp}(t_m) = V_{hp}(t_m) - V_{vs}(t_m) \tag{5-5}$$

$$\Delta V_{hp-3s}(t_i) = \sqrt{\frac{1}{300} \sum_{n=i-300+1}^{i} \Delta V_{hp}^2(t_n)} \tag{5-6}$$

The indices in (5-5) and (5-6) have been evaluated using the same measurement set considered in Figs. 5-5 through 5-9. The results are shown in Figs. 5-10 and 5-11. Individual short-time events appear clearly in the five-minute period covered by this data whereas such short-time events are likely to be masked in the longer time periods considered in the very-short variation indices of (5-3) and (5-4).

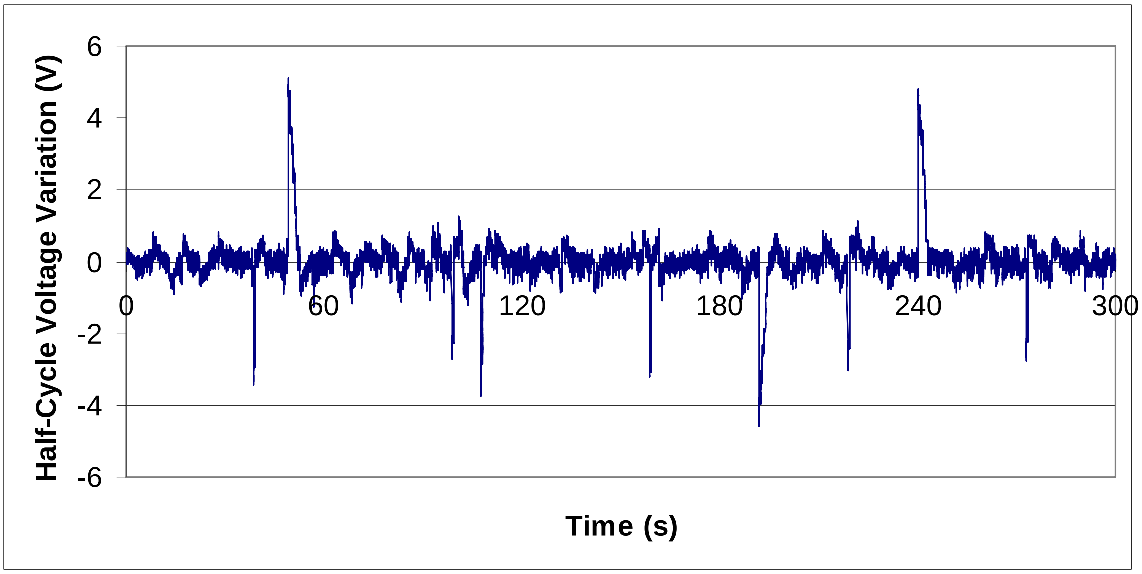


Fig. 5-10. Half-Cycle r.m.s. Voltage Variation

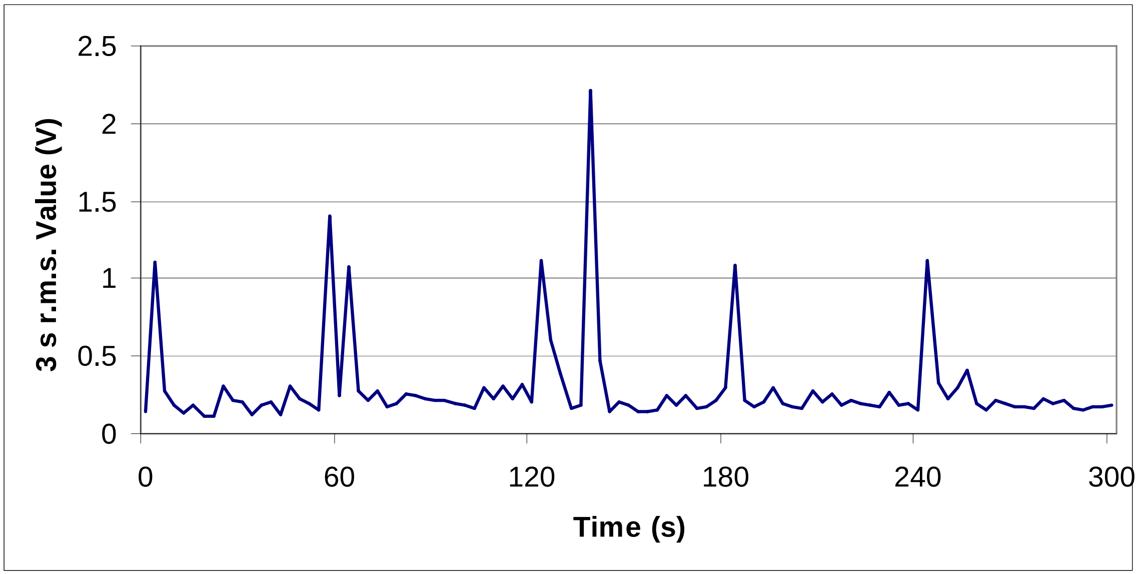


Fig. 5-11. Half-Cycle Voltage Variation 3 s r.m.s. Values

Because the half-cycle indices are intended to capture events occurring in a very small time period, it is appropriate to consider a correlation between the half-cycle voltage variation and the instantaneous flicker sensation, P_{inst}. It is clear from Fig. 5-12 that these two variables are poorly correlated; the most likely reason for this poor correlation is due to the actual time response of the flickermeter algorithm versus the response of the sliding window used to determine the half-cycle variation values.

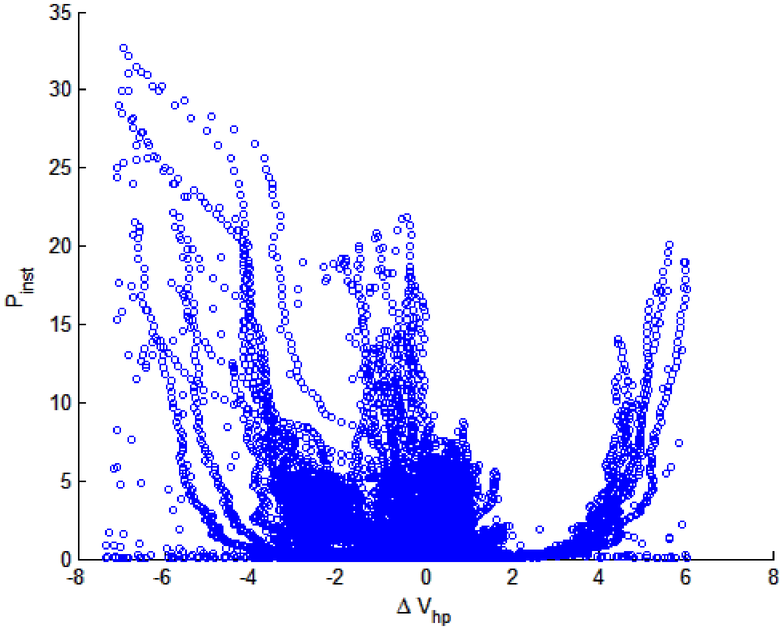


Fig. 5-12. Instantaneous Flicker Sensation versus Half-Cycle r.m.s. Voltage Variation (each variable evaluated every half cycle)

Considering the apparently poor correlation between the proposed indices and the recognized indices for flicker, it appears that the proposed indices offer additional information with regard to voltage quality. Taken as a set, four possible indices can therefore be used to quantify rapid voltage changes in addition to standard flickermeter outputs:

- The ½ cycle variation value (5-5);
- The 3 second ½ cycle variation value (5-6);
- The 3 second (very short) variation value (5-3); and
- The 10 minute very short variation value (5-4).

The first two of these indices may be more suitable for events that occur quickly within a 3 second window and have a relatively low overall repetition rate. Furthermore, the use of a ½ cycle value as a measured index more closely matches typical calculations done for events such as motor starting where the concern is the initial voltage produced by the starting event. The last two of these indices may be more suitable for events that occur more frequently but are perhaps less severe. Such a scenario could arise with distributed generation in MV/LV networks where power variations due to wind changes, for example, lead to slower, smaller, and more continuous voltage variations.

6. Conclusions

The apparent lack of correlation between measured flicker levels and customer complaints has been evaluated using published information, ongoing research, and the experience of the authors of this report. Multiple cases have been documented where high flicker levels have been measured (P_{st}>1) with few if any complaints received. The two main reasons for this lack of correlation are most likely (1) modern lighting is less sensitive to voltage fluctuations and (2) flicker measurements made at HV/EHV locations are likely to be significantly greater than simultaneous measurements conducted at supplied LV locations due to flicker transfer effects.

While modern lighting may be 6-8 times less sensitive to voltage fluctuations than the 60 W incandescent lamp on which the P_{st} concept is based, it is the conclusion of this report that further work is necessary prior to considering modifications of the standardized flickermeter. In many cases, the quantity P_{st} may be used as an overall indicator of voltage quality and any action to "allow increased P_{st} levels to account for modern lighting" could lead to compatibility problems with other equipment. Specifically, further work is recommended to evaluate the sensitivities of other modern end-use equipment to voltage fluctuations to evaluate which (modern) equipment is limiting with regard to voltage fluctuation compatibility levels.

Without considering compatibility issues, it is clear that HV/EHV flicker measurements are often used to incorrectly predict customer complaints. This incorrect usage may appear during either pre- or post-connection studies or assessments and may well lead to over-conservative decisions or requirements. The concept of flicker transfer and accurately accounting for it are central to helping remove conservatism and increasing correlation between measured levels and flicker complaints regardless of the compatibility levels chosen. In this report, it has been demonstrated that HV/EHV flicker levels much greater than the (LV) compatibility level (P_{st} =1) can be allowed without compromising overall electromagnetic compatibility with regard to flicker. Load response, motor load in particular, has been shown to have a marked effect on flicker transfer from its source (typically in HV/EHV) to its ultimate observation (at LV). While the theory behind these effects can become complex, simulation tools are being developed and improved to better take into account the various aspects of flicker transfer.

The final conclusion of this report regards so-called rapid voltage changes. It appears that this special type of voltage fluctuation lacks clear definition and that different procedures are in use by persons and companies involved with studies in this area. Furthermore, there are no standardized measurement methods for the phenomena which, coupled with inconsistent definitions and practices, makes assessment difficult at best. A proposed assessment method, based on published literature, has been presented as a first-pass attempt to move closer to standardization by making use of existing definitions and measurement specifications while retaining the potential to cover the variety of practices presently in use. Further work involving additional measurements is recommended as the next step to further evaluate the proposed assessment method.

7. References

[1] Chinese Standard GB12326-2008.

[2] Guide to Quality of Electrical Supply for Industrial Installations, Part 5, Flicker and Voltage fluctuations, ISBN 2.950 7878-5-1.

[3] D. Arlt, M. Stark, and C. Eberlein, "Examples of International Flicker Requirements in High Voltage Networks and Real World Measurements," Proceedings of the 9th International Conference on Electrical Power Quality and Utilisation, Barcelona, Spain, Oct. 9-11, 2007.

[4] IEEE Standard 1453-2004, "IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems," IEEE, 2004.

[5] A. Robert, M. Couvreur; Recent Experience of connection of big arc furnaces with reference to flicker level; CIGRE 1994, paper 36 - 305 *(CC02 IWD 9516)*.

[6] T.D. Brosnan, M. A. Murray; Voltage fluctuation monitoring in an ESB Transmission station, Irish colloquium on DSP & Control, Dublin, June 1993.

[7] T.D. Brosnan, M. A. Murray; Flicker Severity Measurements on an Electric Arc Furnace during Switched Changes in a Transmission Network, First International Conference on Power Quality, Paris 1991.

[8] D. Arlt, C. Eberlein; Network Disturbances caused by Ultra High Power Electric Arc Furnaces and possible reduction Methods; 4th International Conference of Electrical Power Quality and Utilisation, Krakow 1997.

[9] S. Perera, D. Robinson, S. Elphick, D. Geddey, N. Browne, V. Smith, and V. Gosbell, Synchronized Flicker Measurement for Flicker Transfer Evaluation in Power Systems, IEEE Transactions on Power Delivery, vol. 21, no. 3, July 2006, pp. 1477-1482.

[10] Power Quality Indices and Objectives, WG C4.07 report. CIGRE Technical Brochure 261, Oct. 2004.

[11] IEC/TR 61000-3-7:2008 Electromagnetic compatibility (EMC) – Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems.

[12] Electromagnetic Compatibility (EMC) – Part 4: Testing and Measurement Techniques – Section 15: Flickermeter – Functional and Design Specifications, IEC Standard 61000 - 4 - 15, Edition 1.1, Feb. 2003.

[13] S.M. Halpin, R. Bergeron, R.F. Burch, L.E. Conrad, and T.S. Key, "Voltage and Lamp Flicker Issues: Should the IEEE Adopt the IEC Approach," IEEE Transactions on Power Delivery, vol. 18, issue 3, Jul 2003, pp. 1088-1097.

[14] R. Cai, "Flicker Interaction Studies and Flickermeter Improvement," PhD Thesis, Eindhoven University of Technology, ISBN 978-90-386-1842-5, 2009.

[15] A.E. Emanuel and L. Peretto, "The Response of Fluorescent Lamp with Magnetic Ballast to Voltage Distortion," IEEE Transactions on Power Delivery, vol. 12, issue 1, Jan 1997, pp. 289 – 295.

[16] U. Mader and P. Horn, "A Dynamic Model for the Electrical Characteristics of Fluorescent Lamps," Conference Record of the 1992 Industry Applications Society Annual Meeting, Oct. 1992, pp. 1928 - 1934.

[17] X. Yang and M. Kratz, "Power System Flicker Analysis and Numeric Flicker Meter Emulation," IEEE PES Conference Power Tech 2007, 1-5 July 2007, Lausanne, Switzerland.

[18] S. Perera, D. Robinson, S. Elphick, D. Geddey, N. Browne, V. Smith, and V. Gosbell, "Synchronized Flicker Measurement for Flicker Transfer Evaluation in Power Systems," IEEE Transactions on Power Delivery, Vol. 21, No. 3, July 2006, pp 1477 – 1482.

[19] S. Tennakoon, S. Perera, D. Robinson and S. Elphick, "Attenuation of Flicker by Induction Motor Loads: A Laboratory Study," Proc. IEEE ICHQP 2006, October 2006, Cascais, Portugal, Paper 1A.4.

[20] S. Tennakoon, S. Perera, and D. Robinson, "Flicker Attenuation - Part I: Response of Three-Phase Inductions Motors to Voltage Fluctuations," IEEE Transactions on Power Delivery, Volume 23, Issue 2, April 2008, pp. 1207 – 1214.

[21] S. Tennakoon, S. Perera, and D. Robinson, "Flicker Attenuation - Part II: Transfer Coefficients for Regular Voltage Fluctuations in Radial Power Systems with Induction Motor Loads," IEEE Transactions on Power Delivery, Volume 23, Issue 2, April 2008, pp. 1215 – 1221.

[22] S. Tennakoon, S. Perera, and D. Sutanto, "Flicker Propagation in Interconnected Power Systems," IEEE PowerAfrica 2007 conference, July 16-20 2007, Johannesburg, South Africa.

[23] S Tennakoon, Flicker Propagation in Radial and Interconnected Power Systems, PhD Thesis, University of Wollongong, Australia, 2008.

[24] X. Yang, "Methodology and Simulation Tool for Flicker Propagation Analysis," Joint Conference: Power Quality and Applications, Advanced Distribution Automation, EPRI, July 24 - 26, 2006, Atlanta, USA.

[25] X. Yang and M. Kratz, "Power System Flicker Analysis by RMS Voltage Values and Numeric Flicker Meter Emulation," IEEE Transactions on Power Delivery. vol. 24, no. 3, pp. 1310-1318, July 2009.

[26] P. Kundur, "Power System Stability and Control," ISBN 0-07-035958-X, McGraw-Hill, 1994.

[27] K. Brekke, H. Seljeseth, and O. Mogstad, "Rapid Voltage Changes—Definition and Minimum Requirements," CIRED 2009, Paper 789.

[28] IEC 61000-3-3:2008 Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection.

[29] IEC 61000-3-11:2000 Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤75 A per phase and subject to conditional connection.

[30] IEC 61000-3-5:2009 Electromagnetic compatibility (EMC) – Part 3-5: Limits – Limitations of voltage fluctuations and flicker in low voltage power supply systems for equipment with rated current > 75 A.

[31] IEC 61000-2-2:2002 Electromagnetic compatibility (EMC) - Part 2-2: Environment – Compatibility levels for low-frequency conducted disturbances and signaling in public low voltage power supply systems - Basic EMC publication.

[32] IEC 61000-2-12:2003 Electromagnetic compatibility (EMC) - Part 2-12: Environment – Compatibility levels for low-frequency conducted disturbances and signaling in public medium voltage power supply systems - Basic EMC publication.

[33] M. Bollen, M. Häger, and C. Schwaegerl, “Quantifying Voltage Changes on a Time Scale between 3 seconds and 10 minutes”, CIRED 2005, Paper 287.

[34] IEC 61000-4-30:2003 Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques – Power Quality measurement methods

Annex A. Modifications to the UIE/IEC Flickermeter to Improve Measurement/Complaint Correlation

A.1 Introduction

The measurement results presented in Chapter 3 showed that different lamp types have different flicker responses. However, the UIE/IEC flickermeter was derived by only considering 60W, 230V incandescent lamps. This flickermeter cannot accurately evaluate the flicker level for other lamp types. In this annex, extra flicker response measurement results are presented to show the fact that the light intensity variation amplitude linearly varies with the modulation voltage amplitude for different lamp types within the flicker frequency range of interest. Based on these linearity measurement results, steps to modify the UIE/IEC flickermeter by using different weighting filters for different lamp types is proposed here.

Note that the modifications are based on specific lamp tests and it is not known if the exact results can be generalized. Furthermore, these modifications do not address the fact that voltage changes beyond amplitude modulation may create the traditional flicker sensation (in observers) in modern electronic lighting.

Also note that the flickermeter output $\boldsymbol{P}_{\mathrm{st}}$ is a bona fide measure of voltage quality as far as voltage fluctuations are concerned. Any modification to the flickermeter based solely on observer sensitivity to lamp output variations could result in an overall degradation of voltage quality to the point that the compatibility levels of other (non lighting) equipment are exceeded by the disturbance levels. Such situations should be carefully considered prior to formalizing any modifications to existing flicker measuring instrumentation. The conceptual process of modifying the flickermeter as discussed here is intended only to offer a possible way in which to increase the correlation between measured flicker levels and user complaints.

A.2 Working Principle of Lamps

All lamps convert electrical energy into visible light. However, different types of lamps use different processes to convert the electrical energy into visible light [A-1]. The incandescent lamp converts the electrical energy into electromagnetic radiation by heating the filament when electrical current flows through it. Then the electromagnetic radiation produces visible light and other invisible radiation. The incandescent lamp shows a resistive load characteristic. The lamp voltage and current have a sinusoidal waveform. There is no phase shift between them [A-2]. Measured voltage and current r.m.s. values for a 60 W glass incandescent lamp with varying supply voltages are shown in Fig. A-1. The lamp current increases (or decreases) linearly with the lamp voltage. These results demonstrate the resistive load characteristic of the incandescent lamp [A-3]. The illuminance of the incandescent lamp also has a sinusoidal waveform, which is similar to the waveform of the electrical power of this lamp [A-2].

The voltage/current characteristic of a 15 W fluorescent tube is also shown in Fig. A-1. The current drawn by the tube varies inversely with the tube voltage because of the more "constant power" nature of this type of lighting. Note that the tube voltage is the output of the lamp ballast and is not the same as the input voltage. The input (not tube) voltage/current characteristic for the 15 W fluorescent lamp system would be different from the tube characteristic shown in Fig A-1 as described later as a part of discussion of the working principles of fluorescent lamp systems.

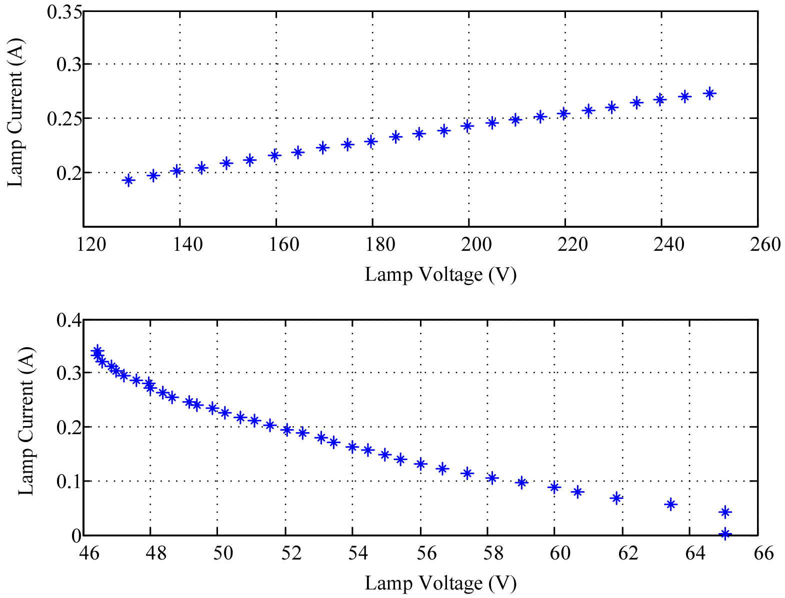


Fig. A-1. The V – I Curve of a 230 V, 60 W Incandescent Lamp (top) and a 15 W Fluorescent Tube (bottom)

The working principle of a halogen lamp is the same as for an incandescent lamp. Specially there is a small inner bulb filled with halogen in the lamp. The tungsten molecules evaporated from the filament make a chemical reaction with the halogen molecules. This reaction results in the tungsten molecules re-depositing onto the filament surface instead of the bulb surface (which is what happens in an incandescent lamp). Thus, the halogen lamp shines brighter at a higher temperature or has a longer lifetime than an incandescent lamp.

Consideration of the working principles of the fluorescent lamp must take into account the fact that the lamp actually consists of two parts: the fluorescent tube and the ballast. The fluorescent tube has a totally different working principle compared to the incandescent lamp. There are two electrodes in the glass tube filled with gas and mercury. A phosphor coating is also used on the inner surface of the glass tube. The electrical current, which passes through the electrodes, excites mercury atoms to release ultraviolet photons. These photons again stimulate the phosphor, which emits visible light photons. The ballast is an important component of the fluorescent lamp set in order to control the tube current. In [A-2], the measured voltage and current of the fluorescent tube is shown. The voltage of the tube is a square wave with switching transients instead of a sinusoidal wave. This voltage shape is caused by the quantum energetic threshold of the excitation of the mercury atoms inside the fluorescent tube, which is related to the energy of the electrons [A-4]. For the fluorescent tube, the energy of the electrons cannot exceed the energy needed for excitation of the mercury atoms. This is due to the fact that the electrons start to lose their energy when the excitations of the mercury atoms become intense. The energy of the electrons increases monotonically with the voltage across the tube. Thus the limitation on electron energy must limit the tube voltage. Therefore, any further increase of the tube current cannot increase the tube voltage and can only increase the light intensity (measured in lumens, lm). With supply voltage (the voltage of the fluorescent lamp set) increasing from 80V to 260V, the voltage across the fluorescent tube decreases from 65V to 45V. The tube current increases from 0A to 0.34A. In general, the tube resistance decreases when the supply voltage increases. This is due to the fact that when the voltage between the electrodes increases, the number of discharged electrons increases, the discharge current increases, and the fluorescent tube resistance decreases.

A.3 Extra Flicker Response Measurement Results

A.3.1 Constant Modulation Voltage Amplitude

These measurements were done by applying sinusoidally-modulated voltage to the lamp and observing the illuminance variation versus the modulation frequency. For the incandescent lamp, the halogen lamp and the energy saving lamp, the applied voltage modulation amplitudes are 0.5%, 1% and 2% based on the 230V voltage level. For the fluorescent lamp set and the CFL with electromagnetic ballast a 3% voltage modulation amplitude is also used. For the LED lamp, 1%, 2% and 3% voltage modulation amplitudes are used. The results of the relative illuminance variations versus the voltage modulation frequencies for different types of lamps are shown in Figs. A-2 - A-7. The relative illuminance variation is calculated by equation (3-3). Sinusoidal modulation was used in each case to produce the results shown in the figures.

The relative illuminance variation of all types of lamps, except for the CFL with electromagnetic ballast, decreases with the voltage modulation frequency. The relative illuminance variation of all lamp types also increases with the modulation voltage amplitude when the modulation frequency is fixed. This is mainly due to the fact that the illuminance of the lamp depends on the thermal emission of the filament or electrode. This process cannot change as fast as the input voltage. The relative illuminance variation of a CFL with electromagnetic ballast increases slightly when the voltage modulation frequency increases. This is due to the fact that the illuminance of this kind of lamp is affected by the electromagnetic ballast. This electromagnetic ballast shows different properties with respect to the electronic ballast under flicker conditions.

Another important conclusion from these measurement results is that the illuminance amplitude variation of the voltage modulation frequency component is linearly proportional to the voltage modulation amplitude for all type of lamps. For further proving this conclusion, linearity measurements have been done for different lamp types.

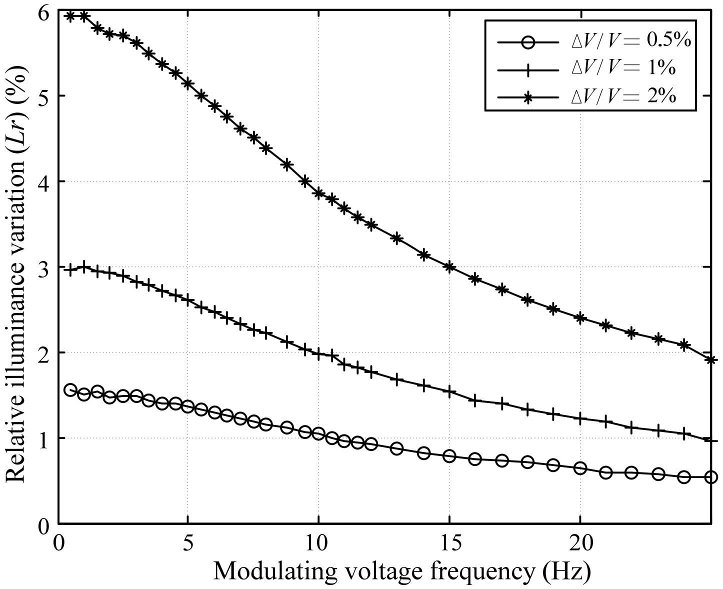


Fig. A-2. Relative Illuminance Variation of a 60 W Incandescent Lamp vs the Sinusoidal Voltage Modulation Frequency

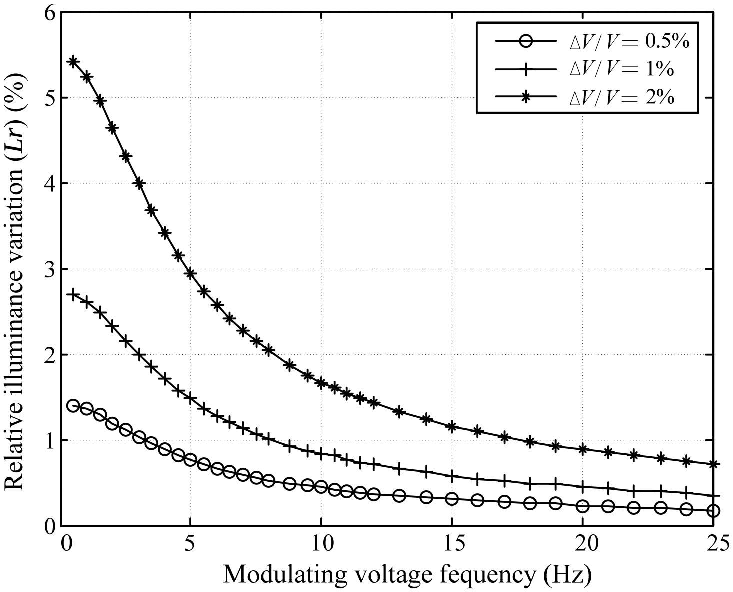


Fig. A-3. Relative Illuminance Variation of a 40 W Halogen Lamp vs the Sinusoidal Voltage Modulation Frequency

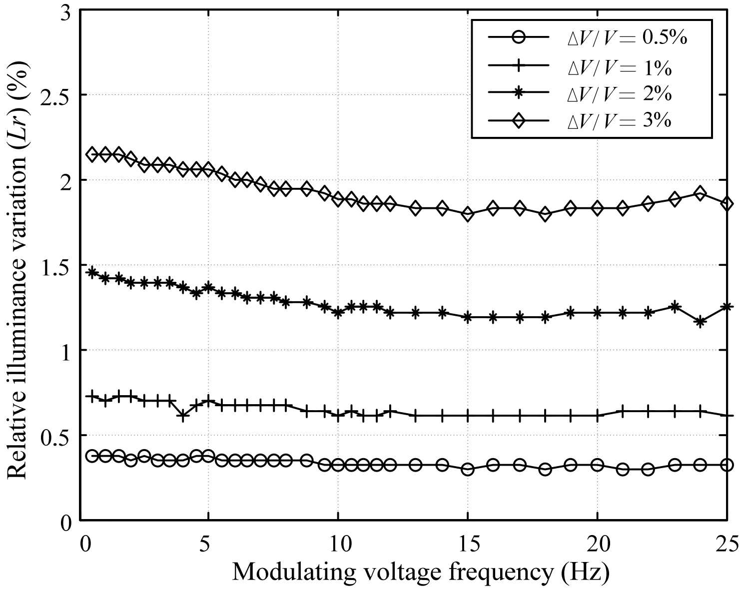


Fig. A-4. Relative Illuminance of a15 W Fluorescent Lamp vs the Sinusoidal Voltage Modulation Frequency

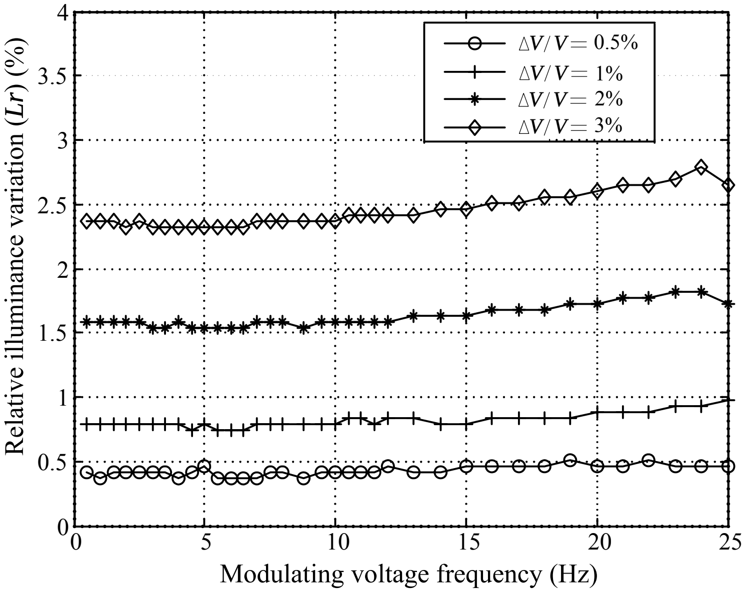


Fig. A-5. Relative Illuminance Variation of a 9 W CFL with Electromagnetic Ballast vs the Sinusoidal Voltage Modulation Frequency

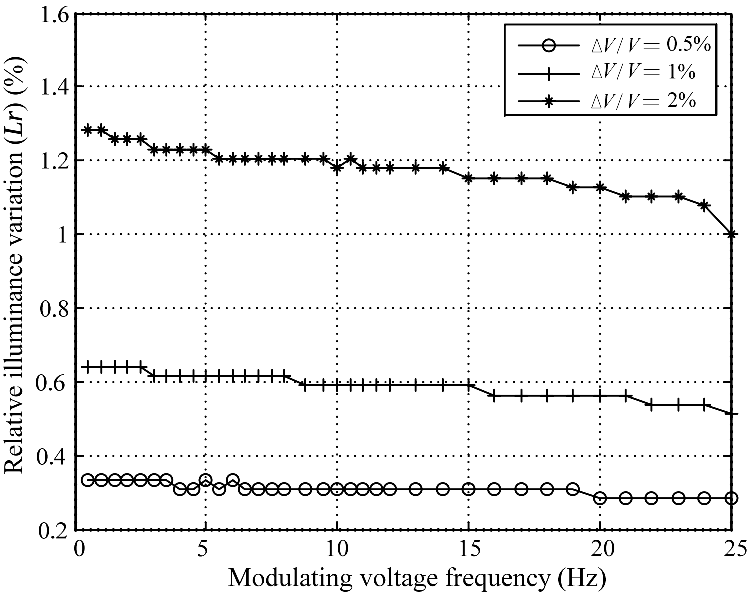


Fig. A-6. Relative Illuminance Variation of an 11 W Energy Saving Lamp vs the Sinusoidal Voltage Modulation Frequency

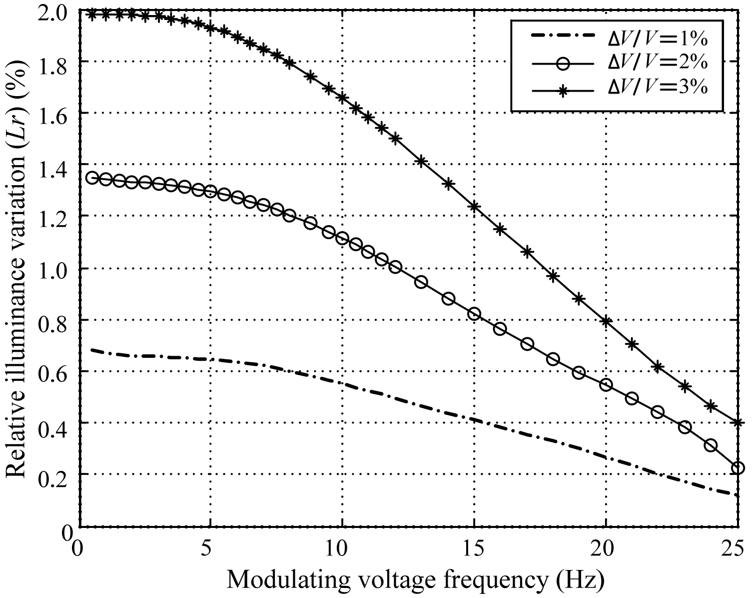


Fig. A-7. Relative Illuminance Variation of a 3.4 W LED Lamp vs the Sinusoidal Voltage Modulation Frequency

A.3.2 Linearity Measurements

These tests are used to evaluate the relationship between the modulation voltage amplitude and the relative illuminance variation when the modulation voltage frequency is kept constant (10Hz). Examples of measurement results for an 11W energy saving lamp and a 3.4W LED lamp are presented in Fig. A-8. The results shown in the figure agree with the conclusion mentioned earlier in that there is a linear relationship between the relative illuminance variation of the voltage modulation frequency component and the modulation voltage amplitude. However, this conclusion has only been validated (by limited testing) within the flicker frequency range of interest (0.5Hz – 25Hz).

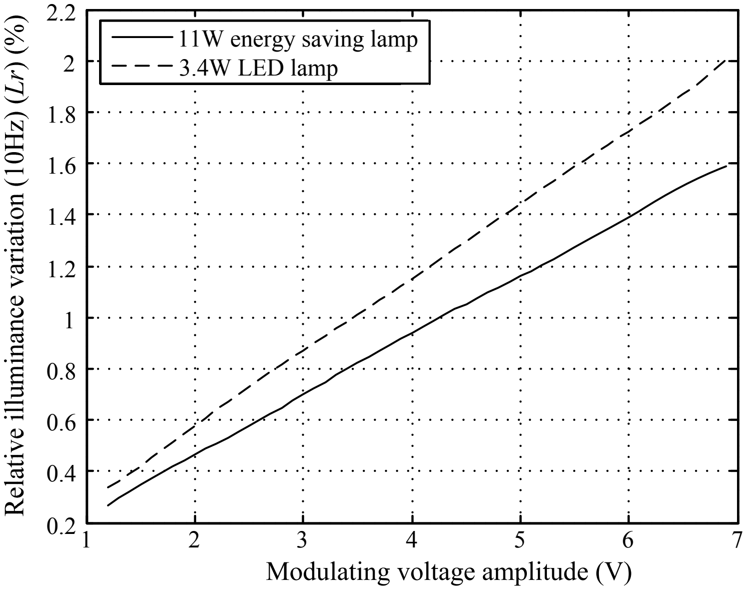


Fig. A-8. Relative Illuminance Variation of 10 Hz vs the Modulation Voltage Amplitude with a 10 Hz Flicker: 11 W Energy Saving Lamp (solid line); 3.4 W LED Lamp (dashed line)

A.4 Proposal to Modify the UIE/IEC flickermeter

Given that modern energy efficient lighting equipment exhibits a markedly different response than incandescent lamps, it is possible that the poor correlation between measured P_{st} values and (other) user complaints is due to lamp response. To evaluate this possibility, the lamp response portion of the flickermeter can be modified to reflect the response of lighting other than the standard 230 V, 50 Hz (or 120 V, 60 Hz) incandescent lamp. Based on the test data presented previously, it is probable that modern lighting is less likely to lead to (other) user complaints due to flicker; greater voltage fluctuations are clearly required with modern lighting in order to obtain the same lamp output variation (with respect to incandescent lamps). It is very important to recognize, however, that modifying the flickermeter to improve measurement/complaint correlation may lead to problems with other equipment or processes because greater voltage fluctuations would conceptually be permitted before the P_{st}=1 level is reached. These greater voltage fluctuations could exceed the compatibility levels of other equipment or processes. Further work in this area is beyond the scope of this report.

In the UIE/IEC flickermeter, the lamp-eye-brain response to the voltage fluctuation is simulated in the weighting filter by the use of a linear transfer function. As shown in Fig. 3-1, this filter can be considered as a combination of two filters: one is the lamp response filter that depends on the lamp type, and the other is the eye-brain filter that depends on the perception of the people who are exposed to the flicker [A-5]. For simplifying the research problem, an identical average eye-brain filter is assumed for all people. The eye-brain filter can be obtained by using the weighting filter of the UIE/IEC flickermeter divided by the incandescent lamp flicker response filter. The parameters of the weighting filter described in the UIE/IEC flickermeter are derived from the flicker response of a 230 V, 60 W and a 120 V, 60 W incandescent lamp [A-6]. The measurement results in Section 3.3 showed the different flicker responses of different lamp types. Thus, a modification of the parameters of the weighting transfer function could be adapted to the lamp type, i.e. different parameters of the weighting filter could be used for different lamp types.

In order to find the parameters of the lamp response filter for different types of lamps, it is necessary to study the relationship between the illuminance variation and the voltage modulation. This can be started with studying the relationship between the voltage modulation amplitude and the relative illuminance variation for each flicker frequency. The measurement results presented earlier indicated that the relative illuminance variation of the voltage modulation frequency component is linearly proportional to the corresponding voltage modulation amplitude within the flicker frequency range of interest (0.5Hz – 25Hz). After Fourier analysis of the measurements of the instantaneous illuminance, it was noticed that the illuminance amplitudes of the voltage modulation frequency components at $100+f_m$ and $100-f_m$ are relatively high (see Table 3-2). As mentioned previously, the frequency components with $100+f_m$ and $100-f_m$ are not the interesting flicker frequencies because the human eye is not sensitive to such high frequencies.

Linear system identification methods can be used to define the transfer function of the lamp flicker response for different lamp types. For each lamp type, a system identification model can be built. The input of the lamp system identification model is the measured modulated voltage amplitude. The output of the lamp system identification model is the measured illuminance variation. To obtain a simple model structure requirement, the OE (output error) model was selected to develop the lamp identification model in one collection of published work. The transfer function derived from the identification model is the mathematical description of the lamp response filter for different lamp types [A-7, A-8].

As discussed, the overall weighting filter of the UIE/IEC flickermeter can be improved for different lamp types by using the linear transfer function of each lamp's flicker response multiplied by the eye-brain flicker response. By implementing these improved weighting filters into the UIE/IEC flickermeter, it may be possible to develop a flickermeter for different lamp types [A-5, A-7]. It is possible that such a modified flickermeter could produce better correlation between measured P_{st} values and customer complaints. It is important to note, however, that other mechanisms more complex than basic voltage modulation could lead to lamp flicker in modern lighting. Such issues should be fully considered prior to any consideration of flickermeter modifications. It is equally important to recall that modifications of the flickermeter to essentially allow greater voltage fluctuations before reaching $P_{st}=1$ will result in an overall degradation of voltage quality. Careful consideration should be given to the widespread use of P_{st} as an indicator of broad aspects of voltage quality; much equipment and many operational practices assume a level of voltage quality associated with $P_{st}<1$ and serious disruptions could occur if voltage quality degradations are loosely permitted.

A.5 References for Annex A

[A-1] J.R. Coaton and A.M. Marsden, Lamps and Lighting, Fourth Edition. New York: John Wiley & Sons Inc., pp.161 – 199, 1997.

[A-2] R. Cai, J.F.G. Cobben, J.M.A. Myrzik and W.L. Kling, “Flicker curves of different type of lamps,” Proceedings of China International Conference on Electricity Distribution, Sep. 2006, Beijing, P.R. China.

[A-3] L. Peretto and A.E. Emanuel, “A Theoretical Study of the Incandescent Filament Lamp Performance Under Voltage Flicker,” IEEE Transactions on Power Delivery Volume 12, Issue 1, pp. 279 – 288, Jan. 1997.

[A-4] E. Gluskin, F.V. Topalis, I. Kateri, and N. Bisketzis, “The Instantaneous Light-Intensity Function of A Fluorescent Lamp,” Physics Letter A, pp. 355-363, March 2006.

[A-5] C.S. Wang; M.J. Devaney, and S.W. Yang, ‘Decomposition of the IEC Flickermeter Weighting Curves’, Proceedings of the 21st IEEE Instrumentation and Measurement Technology Conference - IMTC 04, Vol. 2, pp. 1378 – 1382, May 2004.

[A-6] Electromagnetic Compatibility (EMC) – Part 4: Testing and Measurement Techniques – Section 15: Flickermeter – Functional and Design Specifications, IEC Standard 61000 - 4 - 15, Edition 1.1, Feb. 2003.

[A-7] C. Rong, J.F.G. Cobben, J.M.A. Myrzik, J.H. Blom and W.L. Kling, "Flickermeter Used for Different Types of Lamps", 9th International Conference of Electrical Power Quality and Utilization (EPQU'2007), Barcelona, Spain, Oct. 2007.

[A-8] M. Sakulin, H. Renner, R. Bergeron, T. Key, and D. Nastasi, “International Recommendation for Universal Use of the UIE/IEC Flickermeter,” Proceedings of the UIE XIII Congress on Electrical Applications, 1996.

Annex B. Influence of Flicker Transfer and Attenuation Factors

B.1 Introduction

Rudimentary theory behind flicker propagation, importance and relevance of flicker transfer coefficients, and supporting measurement results are covered in the literature [B-1 – B-5]. These suggest that attenuation of flicker is dependent on a few factors including the composition of loads at various busbars. Particularly, it is stated that mains connected induction motors tend to help attenuate flicker much more strongly than passive loads.

The initial argument behind flicker attenuation provided by induction motors is illustrated through the simple radial system shown in Fig. B-1. The upstream (A) to downstream (B) flicker transfer coefficient [B-4] is considered to be equal to the ratio of the normalized relative voltage changes as given by (B-1).

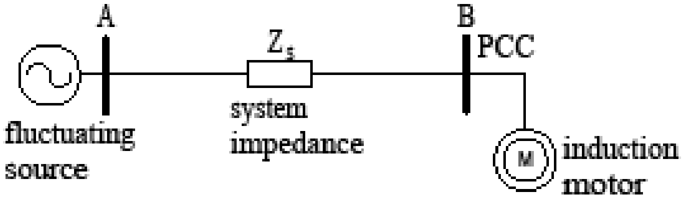


Fig. B-1. Simple radial system

$$T_{\mathrm{PstAB}} = \frac{\dfrac{\Delta V_B}{V_B}}{\dfrac{\Delta V_A}{V_A}} = \frac{1+\dfrac{Z_S}{Z_L}}{1+\dfrac{Z'_S}{Z'_L}} \tag{B-1}$$

In (B-1), the following definitions apply:

V_A, V_B - magnitude of the steady state voltages at A and B respectively;

ΔV_A, ΔV_B - fluctuations in the magnitudes of the voltages at A and B respectively;

Z_L - steady state impedance magnitude of the motor;

Z'_L - effective impedance magnitude of the motor for small voltage fluctuations;

Z_S - impedance magnitude of the system that connects the upstream and the downstream (e.g. transformer impedance); and

Z'_S - effective Z_S (magnitude) for small voltage fluctuations.

It is hypothesised that the effective impedance of the induction motor under fluctuating voltage conditions is less than the corresponding steady state impedance (i.e. $Z'_L<Z_L$) and hence assuming $Z_S=Z'_S$ it is seen from (B-1) that $T_{\mathrm{PstAB}} < 1.0$.

Investigation of flicker propagation in interconnected systems is relatively complex compared to what is applicable to radial systems, primarily arising as a result of the interacting behaviour of the various busbars and the connected loads. Possible methods of analysis for interconnected systems include impedance matrix, load flow, and short circuit methods [B-2]. These flicker transfer analysis methodologies do not take into account the dynamics associated with induction motors in response to voltage fluctuations. Further, these methods are primarily based on the r.m.s. voltage variations in the system and hence do not take the frequency of voltage fluctuations into account in determining the flicker transfer coefficient.

B.2 Response of induction motors subject to voltage fluctuations

The outcomes of studies carried out [B-6 - B-9] to examine how mains connected three-phase induction motors respond when they are subjected to small regular voltage fluctuations are summarized in this section. A range of 60 Hz induction motors [B-10] (220 V/2.2 kW—2.3 kV/1.68 MW) have been investigated. Although the voltage fluctuations that exist in practical networks are random, the systematic investigations that have been undertaken in these studies have been carried out through superimposition (injection) of a single frequency component on the mains supply voltage or through its sinusoidal amplitude modulation.

One significant observation under supply voltage modulating conditions is the fluctuating shaft speed which in fact is seen to influence the stator current fluctuations. These current fluctuations combined together with network impedances can be used to explain the flicker attenuation contribution from induction motors. For the case of positive sequence single frequency injection, the speed fluctuations exhibited by the range of induction machines considered are illustrated in Fig. B-2. It is evident that the behaviour with regard to speed fluctuations can be classified based on the size of the machines. The speed fluctuations in the case of negative sequence single frequency injection have been noted to be relatively insignificant and hence do not seem to have a strong connection with flicker attenuation.

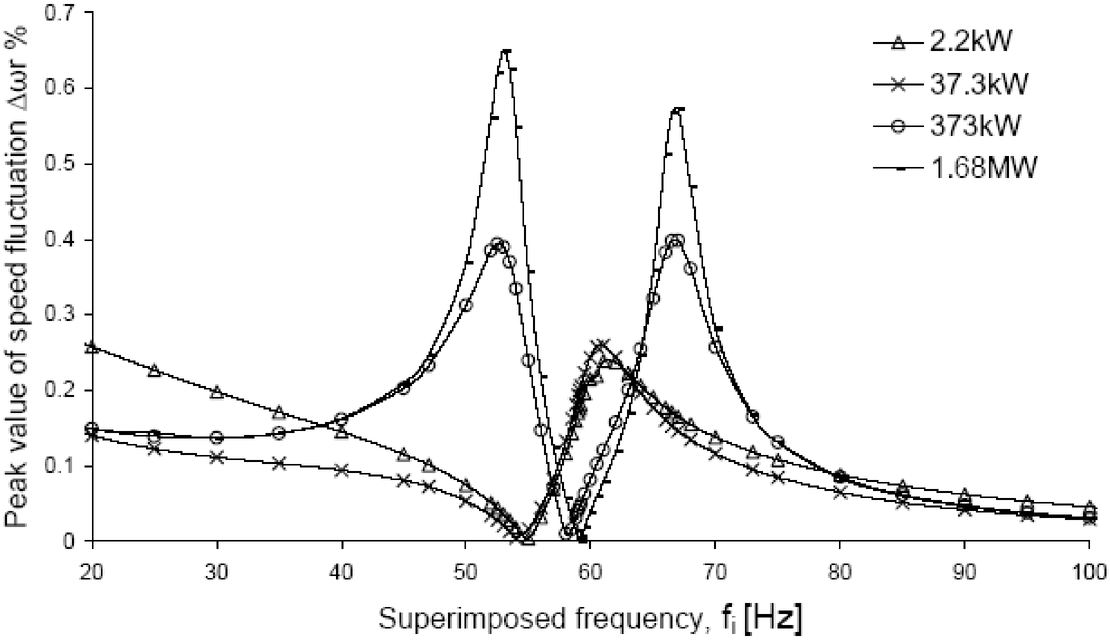


Fig. B-2. Comparison of Rotor Speed Fluctuation of Different Motors with Superimposed Frequency (as % of rated speed)

The fluctuating stator current contains frequency components which either correspond to what is injected or in addition to what is injected (the additional frequency components can be explained using 'multiple armature reaction'). For the case of sinusoidal amplitude modulation of the mains voltage of frequency f_b, at a frequency of f_m, the resulting side band currents for the range of induction machines is shown in Fig. B-3 (expressed as a percentage of the rated current of the motor).

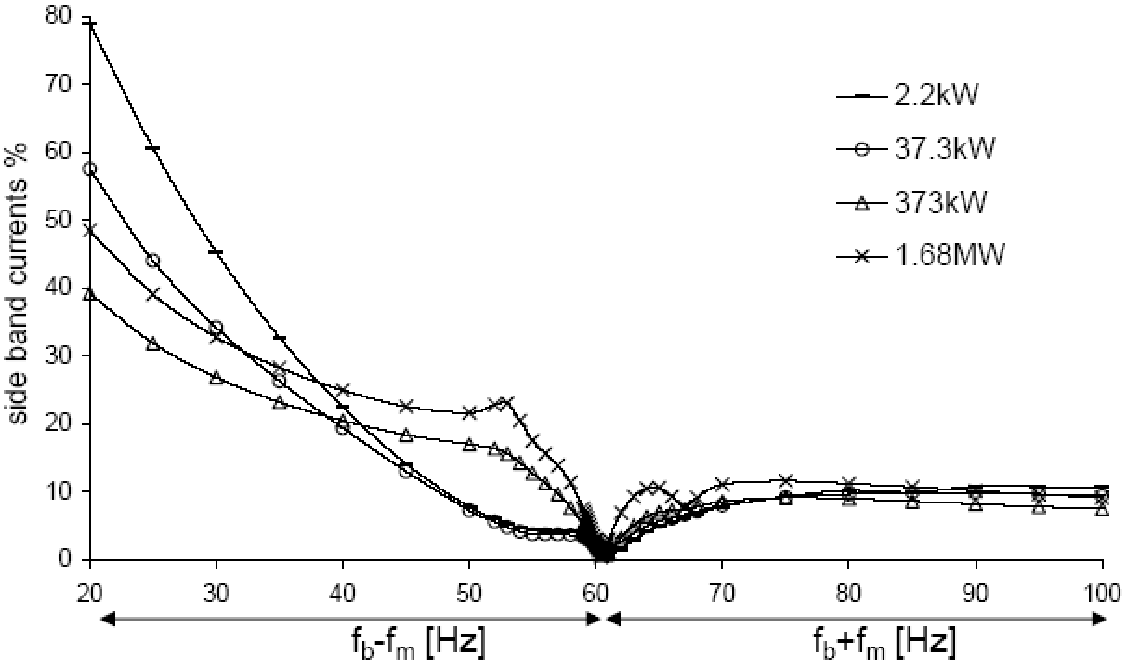


Fig. B-3. Comparison of the Side Band Currents Caused by Amplitude Modulation for Motors of Different Sizes (voltage modulation depth = 5%)

Based on the work presented in [B-6 – B-7], it has been concluded that under fluctuating supply voltage conditions a three phase induction motor exhibits a complex behaviour. It was noted that even for single frequency injection, extra frequency components can appear which may provide some form of damping. As seen, the side band current magnitudes are seen to depend on the modulating frequency. The situation can be even more complex when a modulating voltage has multiple frequency components. This suggests that the flicker transfer factor cannot be assumed to be constrained to a single value in relation to induction machines when there are numerous frequency components present in the modulating voltage.

B.3 Flicker propagation and attenuation in radial power systems

The results of analyses that are presented in [B-6, B-8] which demonstrate flicker propagation and attenuation in radial networks supplying downstream induction motors are presented in this section. Only the case of sinusoidal amplitude modulation is considered where the modulation leads to an upper side band (USB) and a lower side band (LSB) in the voltage spectrum.

Two voltage transfer coefficients can be identified with regard to the two voltage side bands (LSB=lower side band and USB=upper side band) at A and B respectively shown in (B-2) and (B-3).

$$T_{\text{LSB}} = \frac{\dfrac{\Delta V_{BLSB}}{V_B}}{\dfrac{\Delta V_{ALSB}}{V_A}} \qquad \text{(B-2)}$$

$$T_{\text{USB}} = \frac{\dfrac{\Delta V_{BUSB}}{V_B}}{\dfrac{\Delta V_{AUSB}}{V_A}} \qquad \text{(B-3)}$$

In (B-2) and (B-3), V_A and V_B are the steady state voltage magnitudes at A and B respectively. Subscripts "LSB" and "USB" are used to denote "lower side band" and "upper side band," respectively.

For a radial network with a purely inductive system impedance ($\overline{Z}_s = jX_s$) of 3% (of the equivalent impedance of the motor at full load slip), the side band transfer coefficients (T_{LSB} and T_{USB}) have been established with regard to the 1.68 MW induction motor connected at the downstream busbar (B). The variation of T_{LSB} and T_{USB} with the modulation frequency (f_m) over a range of modulation frequencies is illustrated in Fig. B-4.

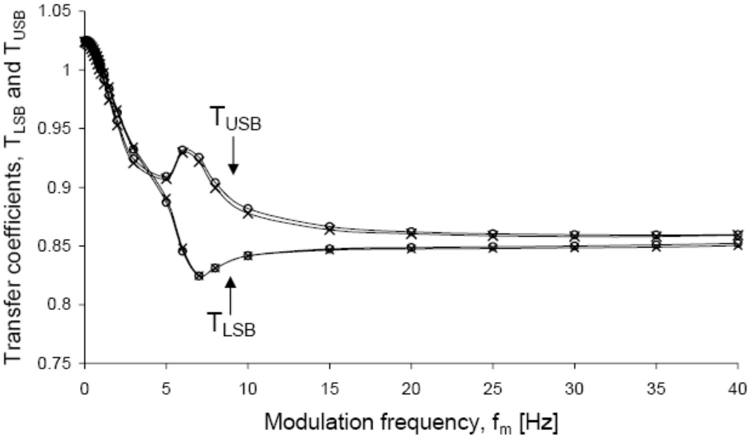


Fig. B-4. Variation of Transfer Coefficients of Voltage Side Bands (T_{LSB} and T_{USB}) with Modulation Frequency (f_m) for the 1.68 MW Induction Machine

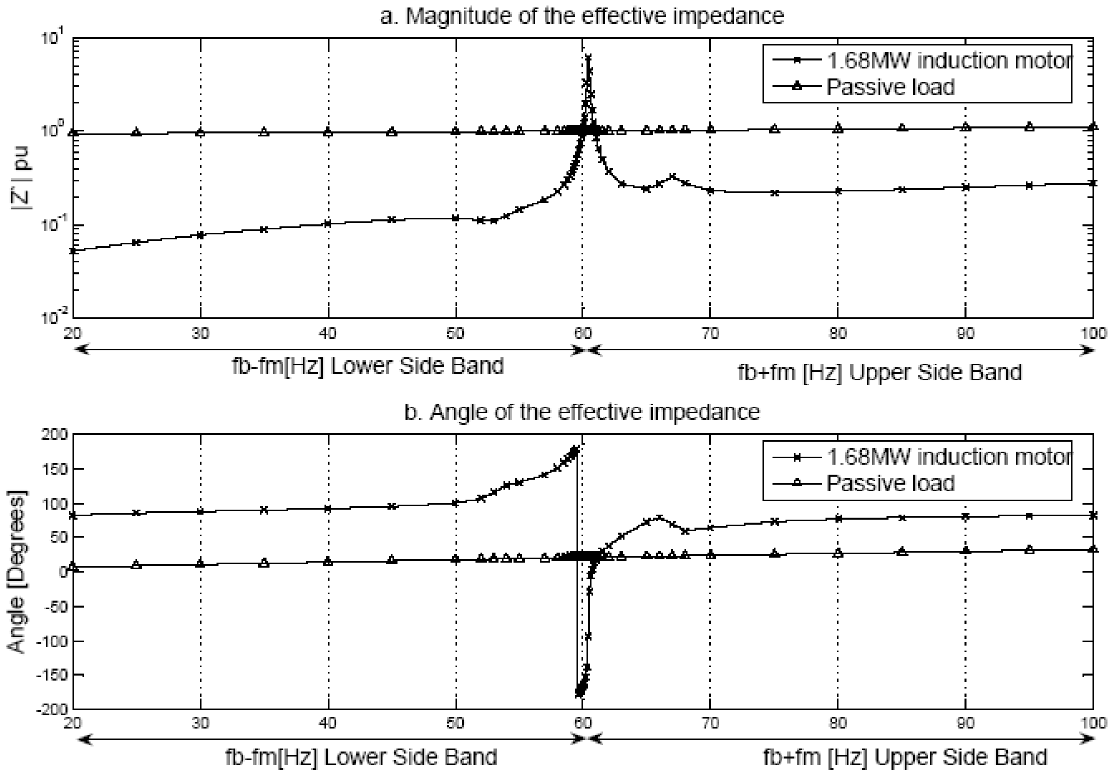
Over a wide range of modulation frequencies, the lower and upper side bands exhibit different attenuation levels where the lower side band is seen to attenuate to a slightly better extent compared to the upper side band for modulation frequencies above 5 Hz. A close examination of Fig. B-4 at low f_m (≤ 1Hz) values reveals that the side bands do not attenuate but rather they get magnified.

The induction motor behavior over the frequency range of interest can be represented by an effective impedance so that the voltage transfer coefficient *T* as given in (B-4) can be established.

$$T = \frac{\dfrac{\Delta V_B}{V_B}}{\dfrac{\Delta V_A}{V_A}} = \frac{|1 + \dfrac{\overline{Z}_s}{\overline{Z}_{motor}}|}{|1 + \dfrac{\overline{Z}_s}{\overline{Z}'_{motor}}|} \tag{B-4}$$

In (B-4), ΔV_A and ΔV_B are the voltage fluctuations at A and B respectively, $\overline{Z}_{motor}$ is the steady state impedance of the motor and $\overline{Z}'_{motor}$ is the dynamic (effective) impedance offered by the motor to the voltage fluctuations. The magnitude and phase angle of $\overline{Z}'_{motor}$ can be used to explain the manner in which the flicker transfer coefficient varies with modulating frequency.

The variation of $|\overline{Z}'_{motor}|$ and its phase angle (ψ) as a function of the frequency of voltage side bands are illustrated in Figs. B-5(a) and B-5(b). The variation of the magnitude and phase angle of a passive impedance (as a function of the frequency of the voltage side bands) that is equivalent to the 1.68 MW induction motor under 60 Hz steady-state conditions is also shown for comparison. The frequency dependant dynamic impedance $\overline{Z}'_{motor}$ can be used to explain the level to which each side band is attenuated (Fig. B-4) at B in comparison to that which exists at A because the system impedance $\overline{Z}_s$ is a static component. Based on (B-4) it can be noted that if $\overline{Z}'_{motor}$ is inductive ($0^\circ < \psi < 90^\circ$ or $90^\circ < \psi < 180^\circ$), the smaller the magnitude of $\overline{Z}'_{motor}$, the better would be the attenuation of the corresponding voltage side band at B. However, if $\overline{Z}'_{motor}$ becomes capacitive ($-90^\circ < \psi < 0^\circ$ or $-180^\circ < \psi < -90^\circ$), regardless of the magnitude of $\overline{Z}'_{motor}$, the voltage side band will be magnified at B.


a. Magnitude of the effective impedance

b. Angle of the effective impedance

Fig. B-5. Variation of (a) the Magnitude and (b) Angle of the Effective Impedance of the 1.68 MW Motor and an Equivalent Passive Load with Frequency of the Voltage Side Band

The complete picture on the flicker attenuation can only be obtained by considering the resultant voltage fluctuation. For regular voltage fluctuations (e.g., sinusoidal modulation as considered previously) the flicker transfer coefficient can be established using the instantaneous flicker sensation values as given by (B-5).

$$T_{P\mathrm{stAB}} = \sqrt{\frac{P_{\mathrm{instB}}}{P_{\mathrm{instA}}}} \tag{B-5}$$

Flickermeters were connected at points A and B in a time domain simulation giving the required instantaneous flicker sensation values for the radial network being studied. A comparison of the voltage transfer coefficients for the two side bands (shown in Fig. B-4) and the flicker transfer coefficient is given in Fig. B-6. A much smoother variation with modulation frequency is noted with regard to the flicker transfer coefficient compared to that exhibited by the two individual side bands. At very low modulation frequencies a flicker transfer coefficient greater than unity is exhibited by the resultant voltage fluctuation as in the case of the two voltage side bands.

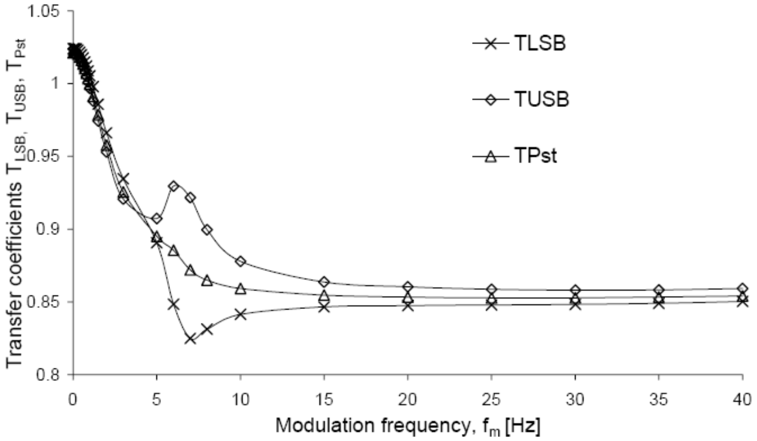
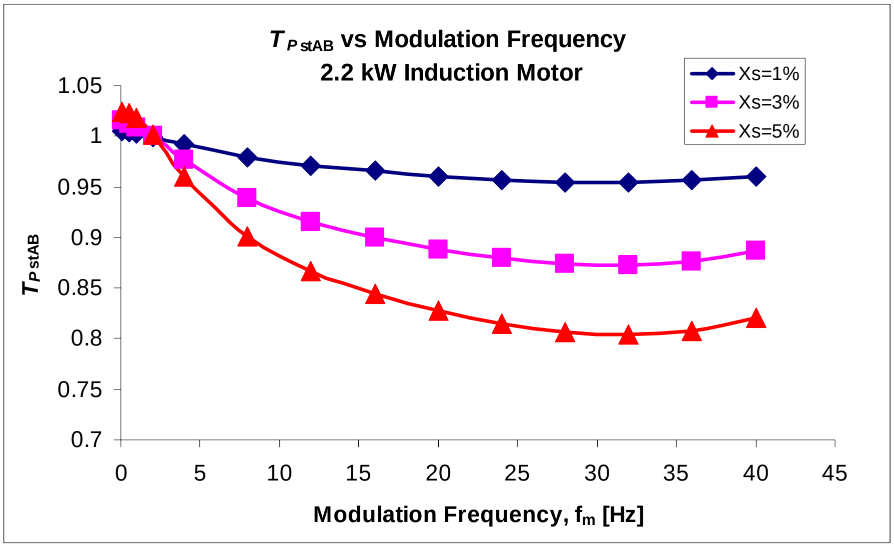
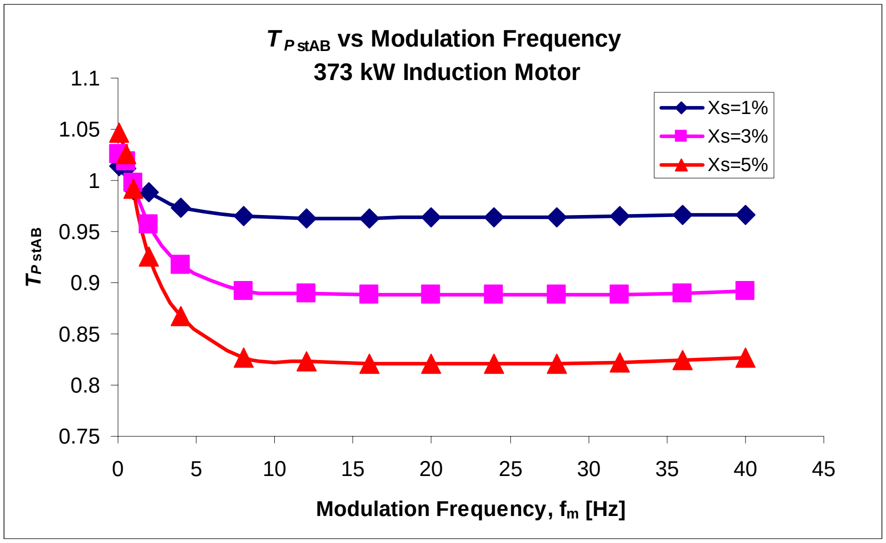


Fig. B-6. Comparison of the Voltage Transfer Coefficients of the Side Bands (T_{LSB} and T_{USB}) and Flicker Transfer Coefficient, T_{Pst} for the 1.68 MW Machine

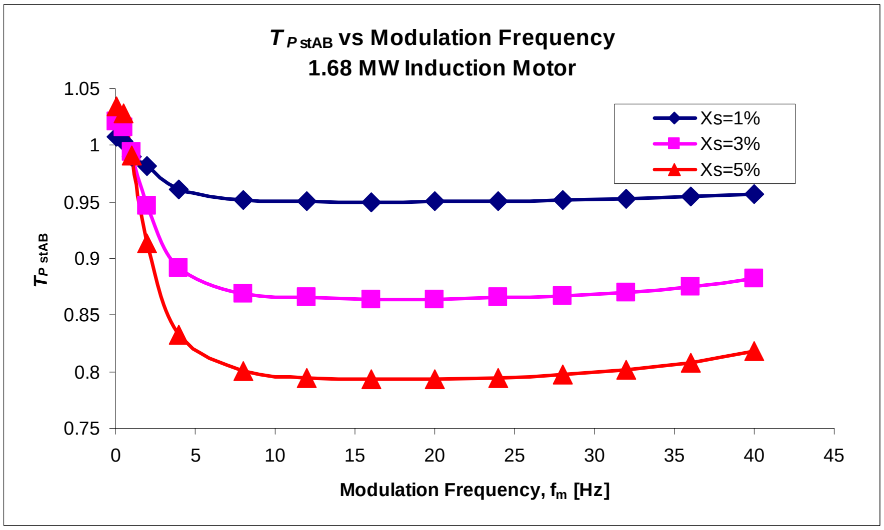
The dependency of the flicker transfer coefficient on the inductive system impedance (Z_S=X_S) also has been investigated. As evident from Fig. B-7, smaller system impedances will yield transfer coefficients closer to unity over the frequency range of interest.



(a)



(b)



(c)

Fig. B-7. Variation of Flicker Transfer Coefficients for Three System Impedance ($\overline{Z}_s = jX_s$) Values for the (a) 2.2 kW, (b) 373 kW, and (c) 1.68 MW Motors

In conclusion, the studies summarized here clearly indicate that the level of attenuation depends on quite a few factors including the frequency of modulation, downstream load composition, and system impedance. For the case of sinusoidal amplitude modulation, although it is possible to develop voltage attenuation coefficients, what is ultimately required is the attenuation of the resultant envelope. It is clear that the attenuation of the resultant envelope follows the trend indicated by the two individual side bands.

B.4 Flicker propagation and attenuation in interconnected power systems

The previously discussed studies have also been extended to examine flicker propagation and attenuation in interconnected power systems [B-9]. These studies also clearly indicate that induction motor loads help attenuate the flicker more effectively compared to passive loads.

B.5 Case study: Flicker Propagation From HV to MV Networks Using a Time-Dependent Load Model in a Hybrid Time/Frequency Domain Calculation Method

Based on the measurements obtained from an industrial site (see Fig. B-8), the hybrid calculation method described in Section 4.3 has been used to evaluate flicker transfer from an HV fluctuating load to an MV location. In this case, the high power flicker source (60 MW EAF located at HV) is modeled directly by site recordings of P and Q every half cycle (i.e. 10 ms). The distribution load in a neighboring MV substation is modeled as a voltage-dependent load (K_v=5) with a high-pass filter time constant T_f=0.5. The flicker levels in different points of this network are determined using a series of frequency-domain solutions where successive solutions (in time) incorporate the time dependent response of the load and the variations in the fluctuating flicker-producing EAF. Using the calculation approach, the flicker transfer coefficient from HV to MV is about 0.82. If the MV distribution load is reduced to 22 MVA, the transfer coefficient becomes 0.9. These results clearly show that flicker attenuation is directly related to load behavior. On-site measurements performed at this location show the transfer coefficient ranging between 0.80 and 0.87 which supports the modeling approach and the selected coefficients.

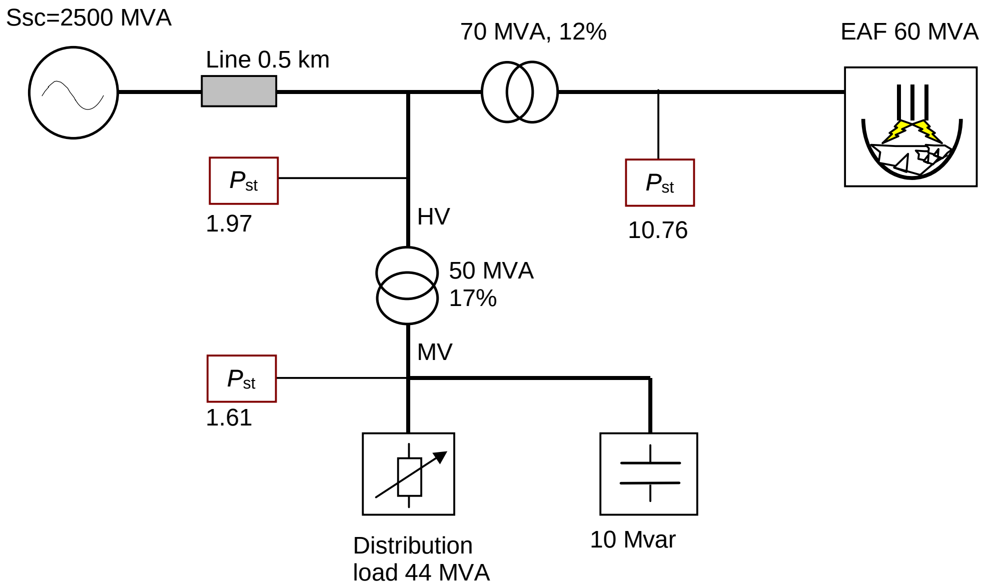


Fig. B-8. HV to MV Flicker Propagation Analysis by Simulation

B.6 References for Annex B

[B-1] E. De Jaeger, G. Borloo and W. Vancoetsem, “Flicker Transfer Coefficients From HV to MV and LV Systems", Proc. 14th International Conference on Electricity Distribution (CIRED97), Session 2, Birmingham, U.K., pp 101-102, June 1997.

[B-2] H. Renner and M. Sakulin, “Flicker Propagation in Meshed High Voltage Networks", Proc. 9th International Conference on Harmonics and Quality of Power, vol. 3, pp. 1023-1028, October 2000.

[B-3] M. C. Simöes, S. M. Deckmann, “Flicker Propagation and Attenuation,” 10th International Conference on Harmonics and Quality of Power, October 2002, Volume 2, pp. 644-648.

[B-4] IEC/TR 61000-3-7, Ed. 1.0 (1996), “Electromagnetic compatibility (EMC) - Part 3: Limits - Section 7: Assessment of emission limits for fluctuating loads in MV and HV power systems.”

[B-5] S. Perera, D. Robinson, S. Elphick, D. Geddey, N. Browne, V. Smith and V. Gosbell, “Synchronised Flicker Measurement for Flicker Transfer Evaluation in Power Systems,” IEEE Trans. on Power Delivery, vol. 21, no. 3, pp. 1477-1482, July 2006.

[B-6] S. Tennakoon, “Flicker Propagation in Radial and Interconnected Power Systems,” PhD Thesis, July 2008, University of Wollongong, Wollongong, Australia.

[B-7] S. Tennakoon, S. Perera, and D. Robinson, “Flicker Attenuation Part I: Response of Three-Phase Induction Motors to Regular Voltage Fluctuations,” IEEE Transactions on Power Delivery, Vol 23, No 2, pp 1207-1214, April 2008.

[B-8] S. Tennakoon, and S. Perera, and D. Robinson, “Flicker Attenuation - Part II: Transfer Coefficients for Radial Power Systems with Induction Motor Loads,” IEEE Transactions on Power Delivery, Vol 23, No 2, pp 1215-1221, April 2008.

[B-9] S. Tennakoon and S. Perera, and D. Sutanto, “Flicker Propagation in Interconnected Power Systems,” Proc. of IEEE PES PowerAfrica 2007, Conference and Exposition in Africa (ISBN: 1 4244 1478 4), July 2007, Johannesburg, South Africa.

[B-10] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, Analysis of Electric Machinery, John Wiley & Sons Inc., 2nd ed., 2002.