Journal of Energy
VOLUME 69 Number 1 | 2020
journal homepage: http://journalofenergy.com/

Denisa Galzina
Croatian Transmission System
Operator (HOPS PrP Zagreb)
Denisa.Galzina@hops.hr

Tonko Garma
FESB, University of Split
garma@fesb.hr

Flicker Spreading In a Transmission Networks

SUMMARY

This paper reports the flicker spreading in the transmission network. Chapter 1 presents introduction containing brief background and key concepts, followed by description of the corresponding instrumentation in Chapter 2. Key contribution of the paper is elaborated in Chapters 3 and 4. Chapter 3 reports measurements of the flicker magnitude along the 400 kV, 220 kV and 110 kV transmission grid for various distances from flicker origin on 400 kV grid, and Chapter 4 gives cost-effective predictive model, enabling estimation of the flicker magnitude for arbitrary selected origin-to-spot distance base on non-linear regression approach. Paper is extension of the work presented at Smagrimet 2019 conference.

KEYWORDS

Short term flicker (Pst), long term flicker (Plt), flicker origins, mitigation techniques, flicker mesurements, prediction model.

INTRODUCTION

According to EN50160 flickers are impressions of unsteadiness of visual sensation induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time.

They are caused by rapid voltage changes, with amplitude much smaller than the sensitivity limit of electrical equipment. It could be said that most of the rapid voltage changes are actually flickers. The voltage flickering as low as 1% of the nominal voltage can already produce significant discomfort, especially if the frequency of the oscillation is between 8 and 10 Hz. [1] The voltage waveform during flicker occurrence measured at local wind power plant is given in Figure 1.

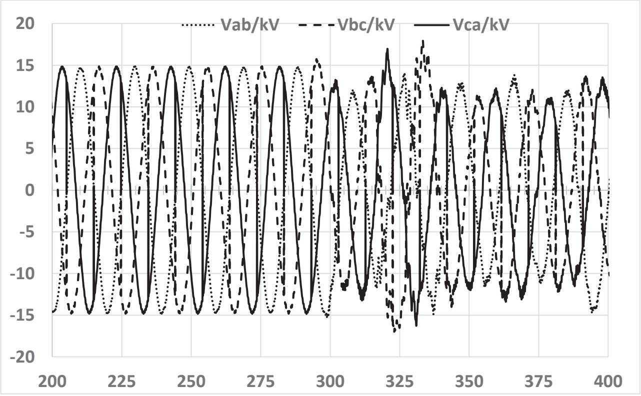

Figure 1. Voltage waveform during flicker occurence

The severity of flicker annoyance is defined by the UIE-IEC flicker measuring method and evaluated using two parameters [2]:

Parameter Pst, (short-term flicker) is measured for each 10-minute interval. Choosing the 10-minute observation period compromises the interval as long enough to prevent the emphasis on isolated cases of voltage variation and at the same time short enough to characterize the voltage changes caused by equipment with short working cycles.

Parameter Plt (long-term flicker) is calculated for a two-hour interval. Plt is derived from 12 consecutive Pst values according to equation:

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

Parameter Plt provides credibility for long-term flicker collection, when one must observe sources with long or variable work cycles, or when multiple sources of flicker work simultaneously in a random order.

Neither Pst nor Plt have a unit, but it corresponds to a limit that should not be passed in order not to cause discomfort the observer for any flicker.

Generally, it can be said that flickers are caused by devices with variable energy consumption, in particular reactive. Changes can occur by turning on or off large capacitive loads or for fluctuating loads, such as arc furnaces, industrial welding machines, or capacitor banks [3].

Various flicker models are reported in the existing literature. Most of them are focusing on the electric arc-furnaces as a dominant flicker occurrence source. In [4] the authors provide single phase arc-furnace model suitable for software-based time and frequency domain analysis. The aforementioned model is extended in [5], applying non-linear approach, based on both sinusoidal and with noise governed arc length variations. More recent study reported in [6] summarizes previous arc furnace models based on both stochastic and chaotic approaches, and introduces the novel method based on voltage simulated by solving corresponding differential equations. This technique enables obtaining voltage-current characteristics and, furthermore, provides an arc current with harmonic spectrum consistent with the measured spectrum. Contrary to these models, eye and head model enable analysis of the flickers originating from various lamps, as reported in [7].

Since the existing literature, as reported in [4-7], focuses on flicker source modeling, or flicker behavior with respect to time [8], we believe this paper, reporting the flicker model enabling valuation and prediction of the flicker magnitude in terms of spot-to-origin distance, may be of interest to for the involved community.

This paper is organized in 5 Chapters. After introduction, flicker meter is briefly described, followed by the in-situ measurements. The crucial contribution of the paper is a model enabling prediction of the flicker magnitude bahvior with respect to corresponding origin distance. Finally, some conclusions are reported at the end of the paper.

FLICKERMETER

This chapter describes main characteristics and specification flicker meters should meet in terms of yielding usefull data. Standard IEC 61000-4-15 provides the functional and design specification for flicker measurement apparatus intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms. [9]

It is important to understand that the primary objective of the IEC flickermeter is not to provide an evaluation of voltage fluctuations but of flicker perception caused by these fluctuations. To achieve this goal, the equipment must be designed so that it can transform the input voltage fluctuations into an output parameter proportionally related to flicker perception. This is possible by simulating the process of physiological visual perception, that is the so-called lamp–eye–brain chain. [10] Figure 2 shows Block diagram of such flickermeter. [11]

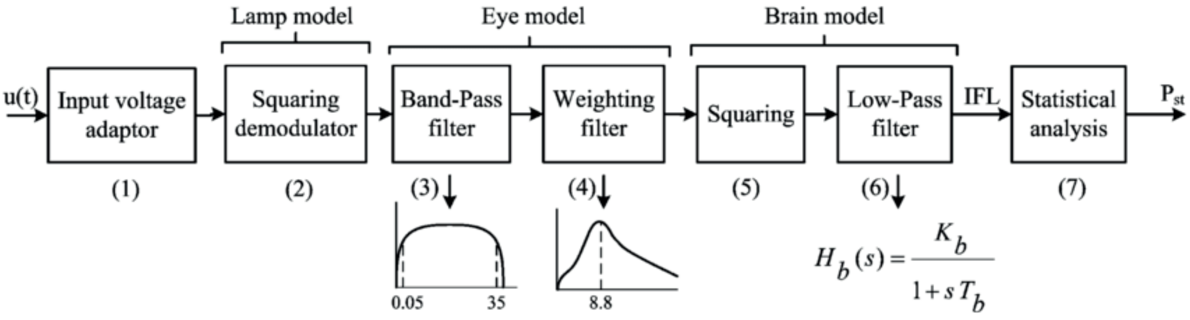

Figure 2. Block diagam of a standard IEC flickermeter [11]

Block 1 of the flickermeter is an input voltage adaptor, which contains a voltage scaling circuit that accepts the supply voltage as an input and derives the relative voltage change.

Block 2 (lamp model part of flickermeter) is squaring demodulator, which recovers modulating signal from the sinusoidal carrier. Blocks 3 and 4 represent eye part of flickermeter. It is composed of a band pass filter and weighting filter. The brain model consist of blocks 5 and 6 – squaring and low pass filter. Squaring multiplier simulates human non-linear visual perception, and filter simulates the storage effect of the human brain. Block 7 conducts statistical analysis, using A/D convertor and classification of results. [11]

EXAMPLE OF THE FLICKER SPREADING MEASUREMENTS THROUGH HIGH VOLTAGE GRID

There are few arc furnaces in the power network of the Croatian Transmission System Operator.

Since the ironworks is in an industrial environment, it is not possible to consistently track the spreading of voltage flickers through the grid. Therefore, we will observe the case of a 400 kV transmission line dropout, because of the relay protection activation. Measurements reported in this chapter are performed using commercially available PQ monitors equipped with the embedded flicker meter option, meeting the requirements reported in Chapter II. The monitors are obtained from well-known and reliable producers providing an extensive factory acceptance tests and warranties. In addition, monitors are regularly maintained in accordance to producer's manuals. In conclusion, set of power-quality measurements obtained using aforementioned devices is not limited in terms of research reported in this paper.

The transmission line was loaded with a current of about 300 A. At the time of the breakdown, the current increased to almost 3000 A (an increase of about 6 times the maximum power demand in that month, and about 10 times the current value immediately before the breakdown), as can be seen in Figure 3. Such an event generated a huge voltage flicker, exhibiting value of 2.7 measured on the 400 kV busbar, Figure 3.

Passing through the transformation of 400/220 kV, the flicker magnitude on the 220 kV side of the transformer decreased below 2 (Figure 4). Further transformation of 220/110 kV causes flicker magnitude to drop to about 1.8, as can be seen in Figure 5.

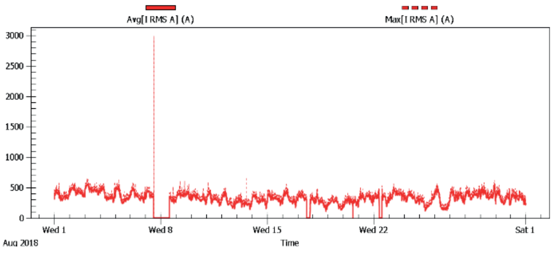

Figure 3. Current values measured at 400 kV transmission line

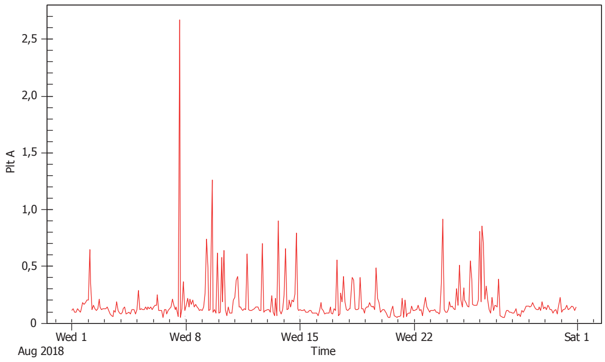

Figure 4. Long term flicker at 400 kV transmission line during breakdown

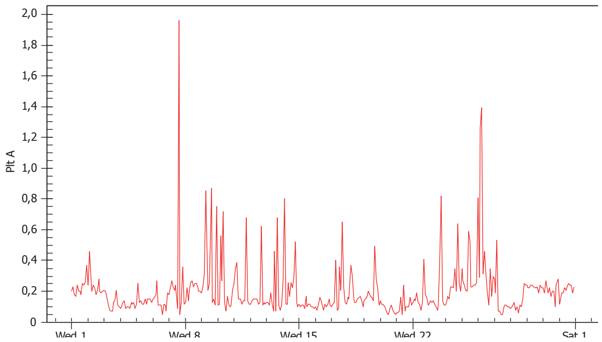

Figure 5. Long term flicker at 220 kV lines after 400 kV lines breakdown

The flickers spread via transmission lines to the other 110 kV transformer stations. The closest station, TS B 110 / X kV, is positioned 9 km away from the source of disturbance, and the next, TS C 110 / X kV, is located 15 km further away, meaning, 24 km from the source. Transformer station D 110 / X kV is placed radially from the source of disturbance at a distance of 11 km.

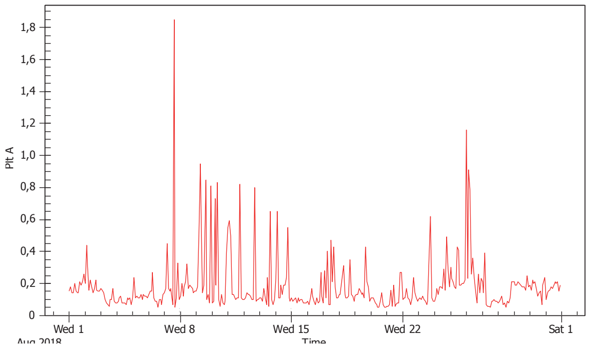

Figure 6. Long term flicker at 110 kV lines after 400 kV lines breakdow^n

At the closest facility, TS B 110 / X kV, the flicker value is almost 1.6 (Fig 6). Upon arrival to the next (15 km distant) TS C 110 / X kV, the flicker value decreases to 1.5 (Figure 7).

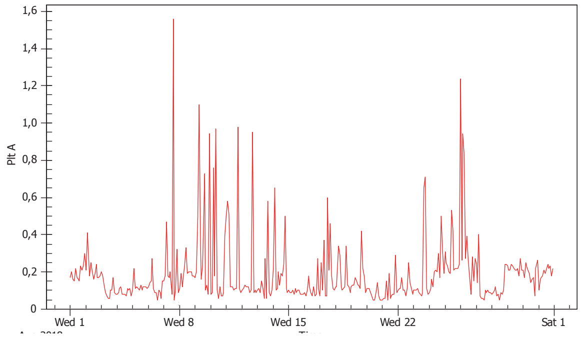

Figure 7. Long term flicker at 110 kV substation TS B, after 400 kV lines breakdown

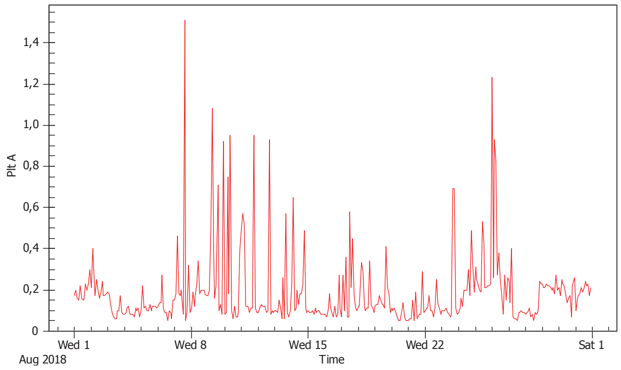

Figure 8. Long term flicker at 110 kV substation TS C, after 400 kV lines breakdown

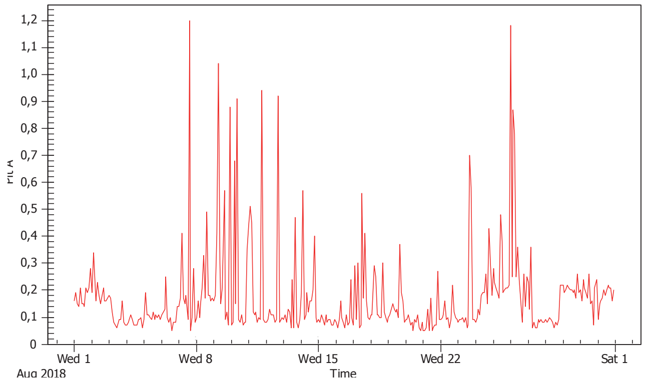

Figure 9. Long term flicker at 110 kV substation TS D, after 400 kV lines breakdown

In the radially located TS D 110 / X kV, 11 km away from the source of disturbance, the flicker value of 1.2 was measured. According to the graphs in Figures 3-8 it can be seen that at stations B and C (located at linearly separated positions) the flicker values decrease uniformly, while in the radially located station C the flicker value is less than what would be expected with respect to the distance from the source of the interference. That is because the substation C is, energetically, a much stronger substation, with transformers of much greater power.

Flicker values for all objects are given in Table 1.

Table I. Overview of Plt flicker according to the metering point

No	Substation	d[km]	S[MVA]	Plt
1	SS 400/220/110 kV	0	2 x 300 1 x 400	2,7 @ 400 kV 2,0 @ 220 kV 1,8 @ 110 kV
2	SS B 110/X kV	9	2 x 40	1,6
3	SS C 110/X kV	24	2 x 20	1,5
4	SS D 110/X kV	11	2 x 60	1,2

PREDICTIVE MODEL

In order to find the correlation between the flicker magnitude at an arbitrary selected location within analyzed transmission grid segment, regression analysis is applied. Analysis is executed upon measured flicker magnitudes obtained from PQ monitors permanently installed in 11 110/x kV substations located from flicker origin at distances up to 80 km.

Linear regression is based on the concept of linear curve describing the measured data. In general case regression curve is given by [12]:

$$\hat{y}= \beta_0+\beta_1 x \tag{3}$$

The optimal line should be selected based on the minimum square criteria, while coefficients 0 and 1 are given by:

$$\beta_1=\frac{\sum_{i=1}^{n} x_i y_i - n\overline{x}\overline{y}}{\sum_{i=1}^{n} x_i^{\,2} - n\overline{x}^2}; \qquad \beta_0=\overline{y}-\beta_1\overline{x} \tag{4}$$

Nonlinear regression is characterized by the fact that the equation depends nonlinearly on one or more unknown parameters:

$$y_i = f(x_i,\ a_i) + \varepsilon_i\ ,\ i = 1,2,\ldots,n \tag{5}$$

where yi, f, xi, ai and εi stand for the response, the known function, the covariant vector, the parameter vector, and the random errors, respectively. [12], [13] In our case f can be defined as exponential function:

$$f = a\, e^{-bd} \tag{6}$$

where *f* stands for the known function, *a* and *b* are coefficients while *d* represents the distance.

Based on the aforementioned approach, empirical model has been developed, enabling predictive analysis of the flicker magnitude for any given transmission system grid point placed between the flicker origin and the furthermost encompassed substation. Results of the model are reported in Figure 10. As it can be seen, the flicker magnitude decreases exponentially with respect to the distance from the origin.

Function describing the flicker behavior is obtained to be:

$$P_{lt} = 1{,}8999\, e^{-0{,}026\, d} \tag{7}$$

where d stands for distance in km and Plt is estimated long-term flicker magnitude. R2 parameter describing the quality of the model estimation exhibits value of 0,9943 out of 1,0000 proving acceptable accuracy and prediction power.

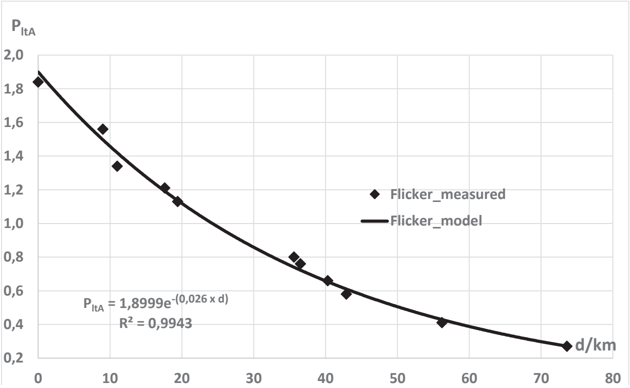

Figure 10. Graphical representation of the model enabling prediction of the flicker magnitude

For example, for a substation located 20 km from flicker origin, measured flicker magnitude is 1,13 while model yields prediction of 1,15 resulting in error of 1,5 %. Worst-case scenario error of less than 7 % obtained at 50 km from the source is attributed to fact that the corresponding substation(s) are linked via not only 110 kV, but also 400 kV lines. Table 2 reports comparison of the measurements and the model. Taking into account exponential decay of the flicker magnitude with respect to the distance from the origin, a linear decrease due to the linear increase of the line impedance could be expected. However, considering the well-known HV over-head power line behavior in transient conditions, observed exponential decay is not a surprise. [14]

Table 2. Comparison of the flicker magnitude obtained by measurements and the model

d[km]	Plt_measured	Plt_model	Error [%]
0,0	1,84	1,90	3,26
9,0	1,56	1,50	-3,62
11,0	1,34	1,43	6,52
17,6	1,21	1,20	-0,64
19,4	1,13	1,15	1,53
35,6	0,80	0,75	-5,89
36,5	0,76	0,74	-3,22
40,3	0,66	0,67	0,96
42,9	0,58	0,62	7,37
56,2	0,41	0,44	7,49
73,6	0,27	0,28	3,82

In addition to the model enabling the prediction of the flicker magnitude, flicker attenuation model is developed, providing the ability to estimate flicker attenuation rate with respect to arbitrary point-to-origin distance. We will define attenuation as follows:

$$A = 20 \log \left(\frac{m_i}{m_0}\right) \tag{8}$$

where *A* stands for attenuation in dB and *mi* and *m0* are flicker magnitudes at arbitrarily selected point (within model scope) and origin, respectively. Assuming the attenuation defined as in eq. 8, the results reported in Figure 10 are obtained.

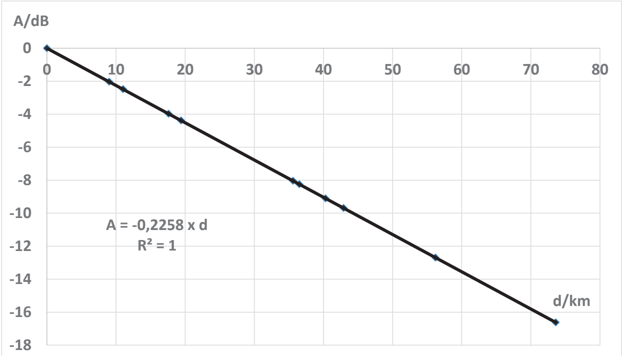

Figure 11. Graphical representation of the model enabling prediction of the flicker magnitude

As it can be seen on the graph, the flicker attenuation (in dB) with respect to the point-to-origin distance (in km), can be estimated as follows:

$$A = -0{,}2258 \text{ x } d \tag{9}$$

where *d* stands for distance in km and *A* is attenuation in dB. R2 parameter describing the quality of the model estimation exhibits value of 1.0 out of 1.0 proving supreme accuracy and prediction power. In other words, flicker attenuation rate is approximately 0,226 dB/km, meaning, flicker relative magnitude will decrease for value of 0,226 dB each km of its distance with respect to origin. According to the proposed model, for a previously mentioned SS located 20 km from the flicker origin, flicker magnitude will be slightly more than 60 % of its initial value.

CONCLUSION

Transmission system operator is obliged to maintain the parameters of voltage quality within the stipulated limits, in order to ensure that all the customers and network users receive the energy of a certain level. Even though flicker is technically not an issue of upmost relevance, customer's frequent complaints to the network operators, can have high financial consequences.

As expected, the measurement results reported in this paper, obtained from various substations within the grid, show clear decrease of the flicker magnitude with respect to source-to-point distance. Furthermore, measured data unambiguously exhibit severe flicker penetration deep into the grid, through multiple voltage levels (from 400 kV, over 220 kV, and then to 110 kV level), and causing the unadmitted levels of flicker in the substations up to 25 km away from the source of the flicker. In addition, aiming towards in-depth analysis of the flicker penetration radii, model based on non-linear regression has been developed, enabling the estimation of the flicker magnitude for any point of known source-to- point distance, contrasting the previously reported models based on flicker source modeling, or flicker behavior with respect to time. Proposed model is low-cost and low time-consuming tool enabling prediction of the flicker severity for analyzed grid segment with reasonable accuracy of 1-3 %. The worst-case scenario error of less than 7 %, obtained for origin-to-spot distance of around 50 km, is attributed to fact that the corresponding substation(s) are linked via not only 110 kV, but also 400 kV lines. Moreover, flicker attenuation model is reported, enabling estimation of the flicker magnitude drop with respect to initial value, and consecutive attenuation rate.

Considering the fact that radii of 25 km encompass up to 10 substations and that model for corresponding distance predicts flicker magnitude approximately 52 % of its initial value, transmission system operator can expect multiple customer's complaints. That forces the operators to maintain their facilities at high standard in order to supply the energy of sufficient voltage level quality.

ACKNOWLEDGMENT

Technical and logistic support of the Croatian Transmission System Operator (HOPS PrP Zagreb) is kindly acknowledged.

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