

Evaluation of Flicker of Light Generated by Arc Furnaces

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Abstract: Due to the dynamic nature of load changes, arc devices are receivers that generate disturbances to the network that affect the power quality. The main disturbance generated by these receivers are voltage fluctuations. One of the effects of voltage fluctuations is the flicker of light caused by lighting receivers. The article presents an analysis of changes indicators flicker of light measured in networks supplying arc furnaces. The propagation of voltage fluctuations to the lines supplying lighting receivers was analyzed. The network parameters influencing the amount of light flicker were estimated. The paper presents a method for calculating the increased flicker of light when several electric arc furnaces are operated in parallel. The conclusions regarding the use of the presented research in practical applications are given in the summary.

Keywords: arc furnace; power quality; voltage fluctuations; flicker of light; statistical evaluation



Citation: Olczykowski, Z.; Łukasik, Z. Evaluation of Flicker of Light Generated by Arc Furnaces. *Energies* **2021**, *14*, 3901. <https://doi.org/10.3390/en14133901>

Academic Editors: Nicu Bizon and Daniel Morinigo-Sotelo

Received: 29 April 2021

Accepted: 23 June 2021

Published: 29 June 2021

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1. Introduction

Arc furnaces are devices that use an electric arc between electrodes and the charge to melt scrap. Arc devices are among the restless receivers of electricity. Due to the unstable operation of the arc furnaces experience rapid changes in power consumption when melting scrap. Very fast changes in the value of the furnace currents cause equally rapid voltage fluctuations in the supply network. In the case of arc furnaces, voltage changes range from a few to several changes per second. Arc furnaces also cause voltage asymmetry and distortion. It is related to the non-linear nature of the electric arc.

The publications [1–7] show the mechanism of the flicker of light, which is the effect of voltage fluctuations. The publication [8] presents, among others, methods of limiting voltage fluctuations through the use of energy storage. A new construction of energy storage devices in a distribution system was proposed. The article [9] presents examples of power systems to which users are connected, causing voltage fluctuations. Analysis of the impact of the short-circuit power in the nodes to which the consumers are connected on the magnitude of voltage fluctuations was carried out. The voltage fluctuations and flicker of light generated mainly by arc furnaces were discussed in [10–14]. Issues concerning the effectiveness of the devices reducing voltage fluctuations and flicker of light in the lines supplying arc furnaces are presented in publications [15–21]. Interesting solution limiting voltage fluctuations using Unified Voltage Conditioner (UVC) was presented in publications [22,23].

The significant contribution of the UIE (International Union for Electricity, previously known as International Union for Electroheat) to the research on voltage fluctuations as a source of the flicker phenomenon should also be emphasized. The effect of many years of research was the development of the concept and implementation for production of a flickermeter [24]. Voltage fluctuations are defined according to the standard [25] as: cyclic changes of the voltage envelope or a series of random changes of the RMS voltage around the nominal value. Flicker of light is a phenomenon related to the influence of voltage fluctuations on lighting receivers. It is defined as a subjective perception of changes in the luminous flux, whose luminance or spectral distribution changes with time. Fluctuations in

the voltage supplying lighting receivers cause changes in the luminous flux. With a certain amplitude and frequency of changes in voltage fluctuations, flicker of light causes people to become nervous up to the level of irritation, beyond which most people are unable to perform any work related to the perception of small objects, poorly contrasting with the surrounding background. In some cases, light flicker may trigger epilepsy attacks [26].

Flicker of light is a phenomenon that is purely physiological. Voltage fluctuations causing perceivable flickering of light are very difficult to determine objectively. Flickering to which the eye of one person is sensitive may not be noticed by another person [27,28].

Figure 1 shows the formation and perception of flicker of light caused by arc furnaces. The currents in the supply line to arc furnaces change rapidly (ΔI). As a result of changes in currents on the impedance of the transformers and the furnace supply line, rapid voltage fluctuations (ΔU) occur.

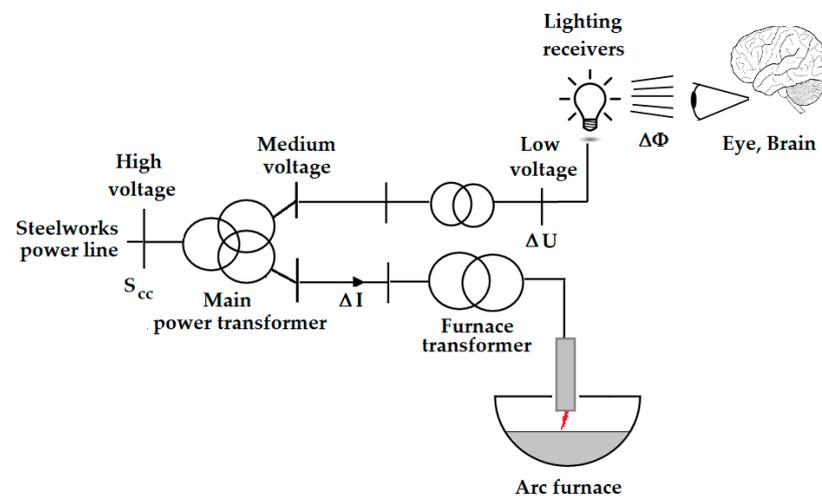


Figure 1. The development and perception of flicker of light caused by arc furnaces.

Voltage fluctuations propagate to the supply network and other lines inside the steelworks, including circuits containing lighting receivers—Figure 2. Changes in the voltage supplying lighting receivers cause changes in the luminous flux ($\Delta\Phi$), which at a certain amplitude and frequency of changes are noticeable by the human eye, causing the negative effects described above. UIE has established a Committee for the Study of Disturbances (S.C.), composed of experts from various countries. This committee undertook research aimed at assessment of various types of voltage fluctuations, including irregular and time-varying ones, and development of a universal measurement method and regulations for connecting non-static loads to the network. In the first years, several series of comparative measurements were carried out, using measuring devices developed in different countries, to assess their advantages and disadvantages. The effect of long-term experimental and theoretical research was the development of a device for measuring flicker of light, called UIE-flickermeter [29,30].

The purpose of measuring flicker by using a flickermeter is to quantify the degree of flickering caused by changes in the luminous flux due to voltage fluctuations. The input signal of the meter is the voltage measured at the point at which the level of flickering light is assessed. The further operation of the meter is to model the “lamp–eye–brain” system. The measuring device is designed to reproduce the physiological disturbances felt by the person receiving the flux changes produced by the reference lamp, which is a 60 W/230 V bulb.

Two dimensionless quantities form the units of measurement for flicker: short-term flicker severity P_{st} and long-term flicker severity P_{lt} .

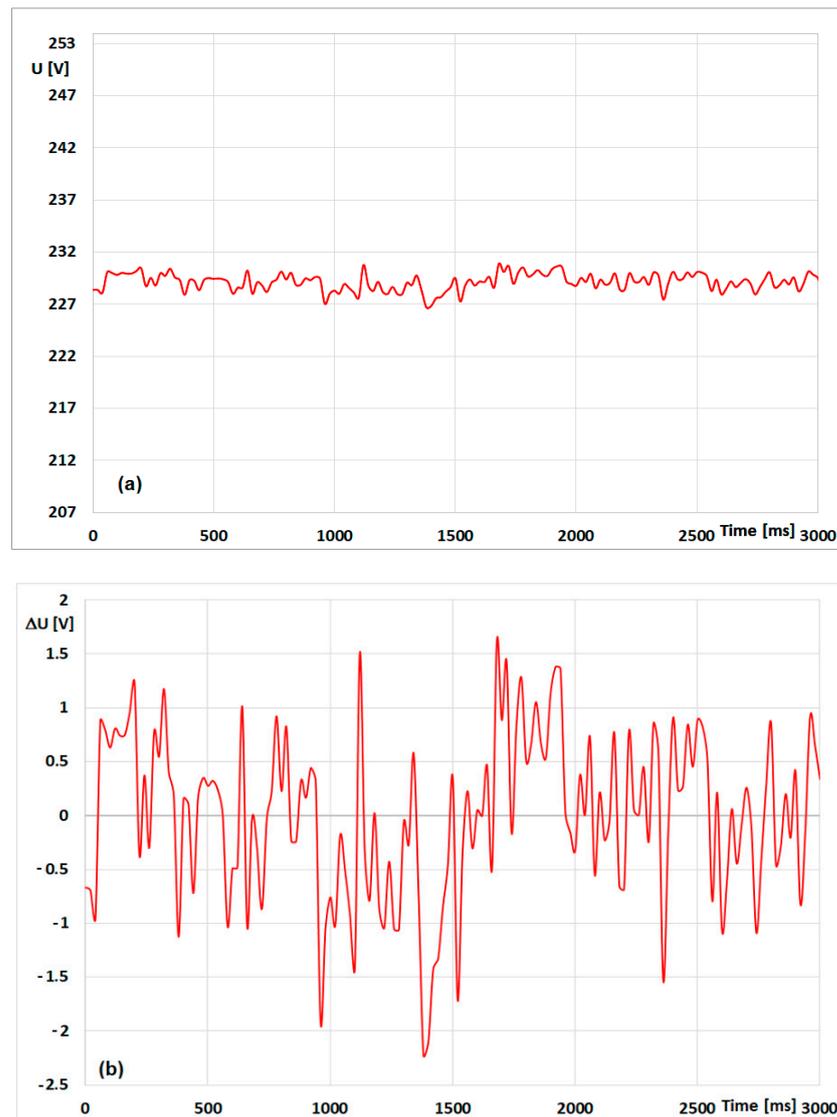


Figure 2. RMS value changes (a) and voltage fluctuations (b) recorded in the power supply line lighting receivers.

The long-term flicker severity P_{lt} is determined on the basis of the following twelve short-term flicker P_{st} indicators from Formula (1):

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{st}^3}{12}} \quad (1)$$

The short-term flicker P_{st} is determined in a ten-minute period. From the twelve P_{st} values, the long-term flicker rate P_{lt} for a period of 2 h can be calculated.

Currently, measurements of flicker indicators provide the best way to identify a voltage disturbance that results in the flicker phenomenon. In the case of arc furnaces, the cause of flickering light is voltage fluctuations, the source of which is an electric arc dynamically changing its parameters. The flicker severity assessment uses the direct measurement of flicker indices, and the values of the long-term flicker P_{lt} are compared with the permissible levels given in the relevant standards and regulations [31–34].

The aim of this article is to evaluate the flicker of light as a result of voltage fluctuations generated by arc furnaces in the power system. In order to estimate network parameters influencing the amount of light flicker, steel plants with different supply conditions (different

short-circuit powers) were selected. Several measurement cycles of indicators characterizing the power quality were carried out. Both ten-minute and ten-second measurement intervals were used to record the flicker indicators. The use of measurement intervals of several seconds allowed for a detailed analysis of the impact of arc furnaces on the power system during individual melts. A method for calculating the increase in light flicker in the case of parallel operation of several electric arc furnaces is proposed. The presented method was compared to the method recommended by UIE. In the discussion chapter, reference is made to the Commission Regulation (EU) 2019/2020 European Parliament in relation to the proposed light flicker index PstLM for LED and OLED MLS.

2. Measurement of Flicker of Light Indicators

Measurements of flicker indicators in real conditions allow the best assessment of the influence of voltage fluctuations generated by arc furnaces on the formation of the flicker phenomenon. Figure 3 shows the power supply diagram of a steel plant with an electric arc furnace (EAF) with a transformer capacity of 20 MVA and a device for secondary steel processing (ladle furnace—LF) with a transformer capacity of 5 MVA. Figure 3 also shows the connection points of electricity quality analyzers. The following analyzers were used in the research: Memobox 686, Memobox 800 and QWave. A computer measuring system was used to record the voltage and current waveforms. The flicker of light indicators were registered simultaneously at four points: Point A ($U_n=110\text{ kV}/S_{SC}=5000\text{ MVA}$)—the main line supplying the smelter, Point B ($U_n=30\text{ kV}/S_{SC}=750\text{ MVA}$)—supply line for the arc furnace (EAF), Point C ($U_n=6\text{ kV}/S_{SC}=500\text{ MVA}$)—supplying the ladle furnace (LF), Point D ($U_n=230\text{ V}$)—circuits supplying lighting receivers. Measurements were made both in long measurement periods (including one week of recording) and short measurement periods for individual melts in the arc furnace. Ten-minute measurement intervals were used for the weekly recording cycle and five-second intervals for the recording of individual melts. Conducting the tests with shortened time intervals (5 s and 10 s) was aimed at more precise determination of changes in the light flicker indicators during the smelting. Parallel to the measurements of light flicker indicators, other parameters characterizing the quality of electricity were recorded.

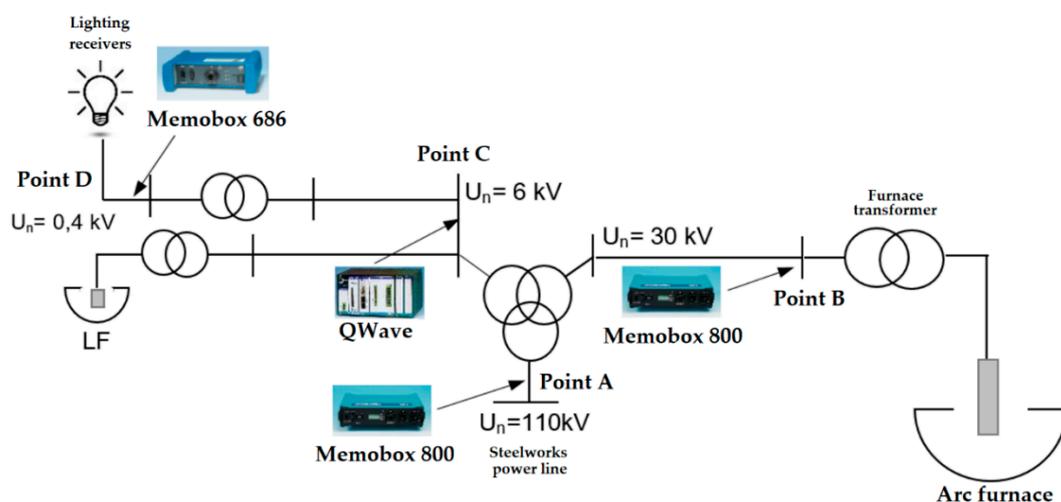


Figure 3. Places of measurement of voltage fluctuations and flicker indicators.

The article also presents an analysis of disturbances caused by arc devices in a steelworks powered by a $U_n = 400\text{ kV}$ line with a short-circuit power of $S_{SC} = 8774\text{ MVA}$. The steel plant is powered by a line with a voltage of $U = 110\text{ kV}$ and a short-circuit power $S_{SC} = 1512\text{ MVA}$.

On the basis of the recorded data of electricity quality parameters, the following were obtained: evaluation of the propagation of disturbances caused by arc furnaces

(mainly light flickering phenomena), statistical analysis of changes in light flicker indices, estimating the value of the K_N coefficient determining the increase in voltage fluctuations with a different number of arc devices working in parallel.

Direct measurement of flicker indicators, simultaneously at several points in the energy system, seems to be the easiest way to determine propagation. However, it has some limitations. First of all, this method of propagation analysis uses several light flicker meters (in the case of an extensive energy system), the unit price of which is quite significant. Secondly, this method must have several measuring points available at the same time, in which the meters must be time-synchronized with each other. The indirect (computational) method is used to determine the change of voltage fluctuations on the basis of the network parameters and the light flicker indices registered at the reference point. The considered system takes into account the case where the network is of the radial type and the flicker source is connected at the end of the track (single furnace or group of furnaces). The advantage of the presented method is mainly due to the fact that the flicker emission of the considered disturbed load relates directly to the short-circuit power of the network. The UIE guide suggests, as a compromise between the required accuracy and difficulties in obtaining measurement data, the use of an approximate assessment based on the short-circuit power ratio at the points in the network under consideration [5].

3. Propagation of Disturbances Generated by the Arc Furnace

Issues related to the propagation of disturbances caused by arc furnaces have been presented, among others, in publications [35–38]. Assessment of the individual emission of voltage fluctuations caused by a single arc furnace, at different voltage levels, can be made on the basis of direct measurements of the flicker indicators. In this way, the actual propagation transfer coefficient $TC_{P_{st}AB}$ is defined [39].

$$TC_{P_{st}AB} = \frac{P_{st}(A)}{P_{st}(B)} \quad (2)$$

Figure 4 shows changes in short-term flicker P_{st} measured during one week at point A (110 kV line supplying the steelworks) and point B (30 kV line supplying EAF)—Figure 3.

The correlation coefficient between the short-term flicker severity P_{st} recorded at the voltage level: 110 kV and 30 kV is 0.86. Based on Formula (2), the following were determined: $TC_{P_{st}AB_{max}} = 0.18$ and $TC_{P_{st}AB_{95\%}} = 0.17$.

Figure 5 shows the short-term flicker P_{st} waveforms measured during one smelting process at point A (110 kV line supplying the steel plant) and point B (30 kV line supplying EAF).

The correlation coefficient between the short-term flicker severity P_{st} recorded at the voltage level: 110 kV and 30 kV is 0.98. Based on Formula (2), the following were determined: $TC_{P_{st}AB_{max}} = 0.20$ and $TC_{P_{st}AB_{95\%}} = 0.19$.

The basic parameters for determining voltage fluctuations in point A (Figure 3) there are short-circuit powers $S_{SC}(A)$, $S_{SC}(B)$ and $P_{st}(B)$ —indicators of short-term flicker of light measured at the reference point. The TC_{AB} propagation coefficient can be calculated from the Formula (3):

$$TC_{AB} = \frac{S_{SC}(B)}{S_{SC}(A)} \quad (3)$$

Substituting into the formula (B) the values of the short-circuit powers in points A (Figure 3)— $S_{SC}(A) = 5000$ MVA and B; $S_{SC}(B) = 750$ MVA—we get:

$$TC_{AB} = \frac{S_{SC}(B)}{S_{SC}(A)} = \frac{750}{5000} = 0.15 \quad (4)$$

which allows for the determination of the theoretical values of the index in point A on the basis of measurements at point B:

$$P_{st}(A) = P_{st}(B) \times 0.15 \quad (5)$$

Figure 6 shows changes of P_{st} short-term flicker severity recorded simultaneously during one week of measurements at three points: steelworks supply line—point A, EAF supply line—point B, LF supply line—point C.

In Figure 7, the waveforms of light flicker indicators measured in the supply network of the steel plant $P_{st_Point B}$ and the supply network of the steelworks $P_{st_Point A_cal}$ were presented, as well as the theoretically determined by the Formula (5)— $P_{st_Point A_cal}$. Only the $P_{st_Point-meas}$ and $P_{st_110\text{ kV-cal}}$ indicators are compared.

Figure 8 shows changes of P_{st} short-term flicker severity recorded simultaneously during one week of measurements at two points: steelworks supply line ($P_{st_Point A_meas}$), EAF supply line ($P_{st_Point B_meas}$) and determined by Formula (5) ($P_{st_Point B_cal}$).

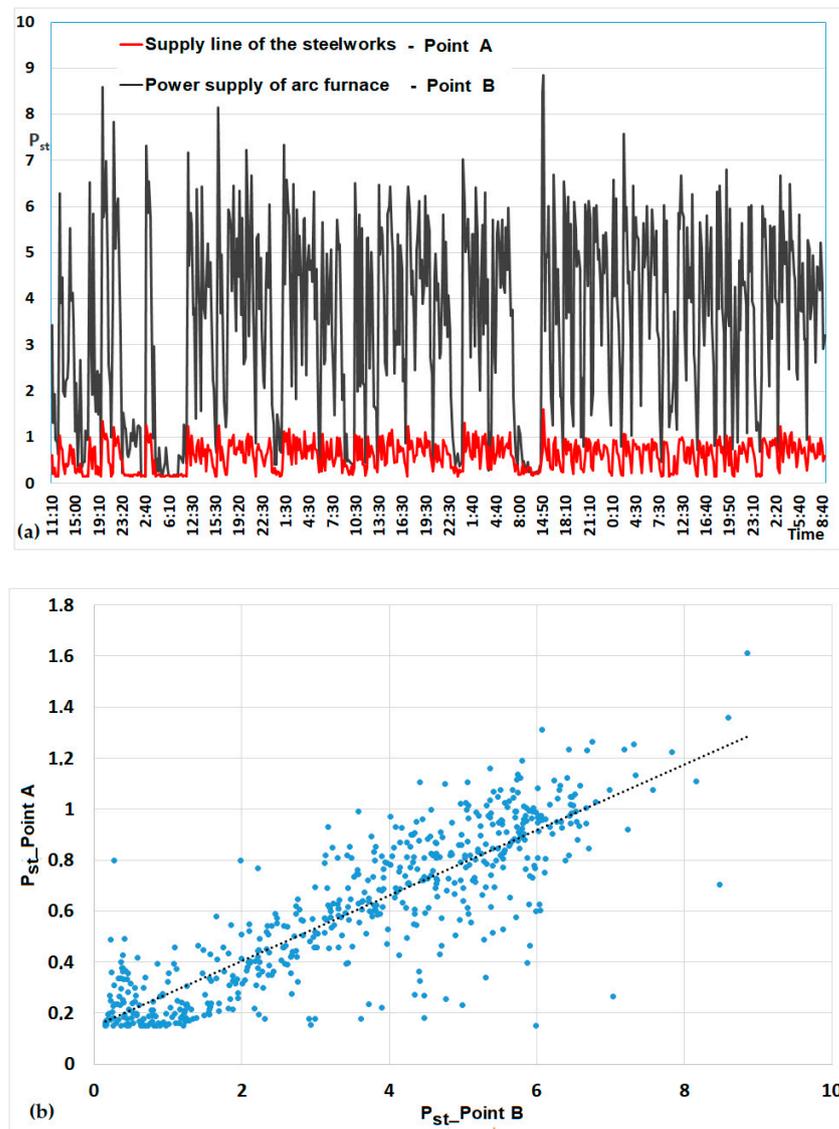


Figure 4. Changes of P_{st} short-term flicker severity recorded simultaneously during one week of measurements at two points: steelworks supply line—point A, EAF supply line—point B (a); correlation between the flicker P_{st} Point A and Point B (b).

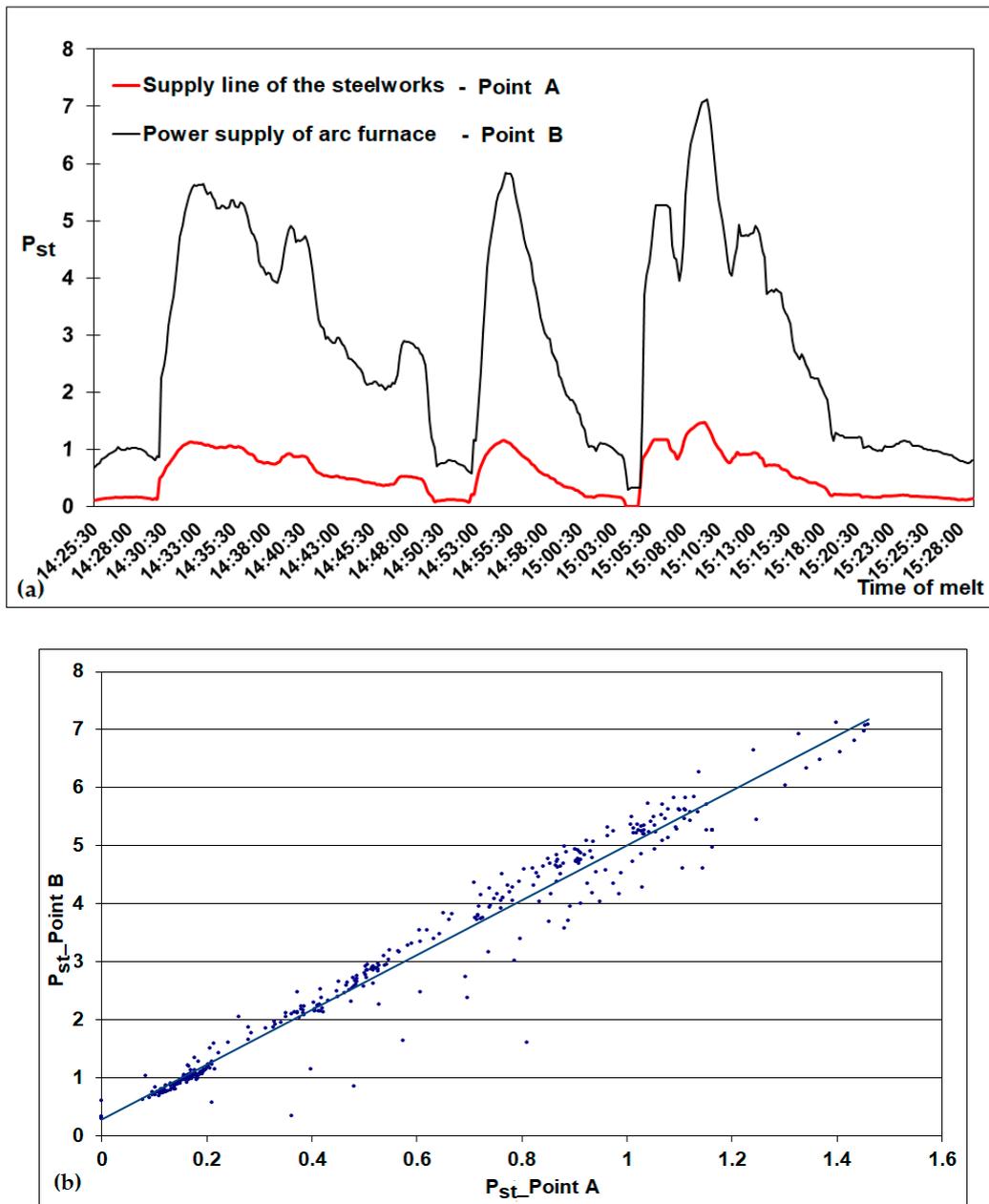


Figure 5. Changes of P_{st} short-term flicker severity recorded simultaneously during one smelting of measurements at two points: steelworks supply line—point A, EAF supply line—point B (a), correlation between the flicker P_{st} Point A and Point B (b).

The article also presents an analysis of disturbances caused by arc devices in a steelworks powered by a 400 kV line with a short-circuit power of $S_{SC} = 8774$ MVA. The steel plant is powered by a line with a voltage of $U = 110$ kV and a short-circuit power $S_{SC} = 1512$ MVA. There are three arc furnaces and two ladle furnaces operating in the steelworks.

The flicker indicators were measured at the voltage level of 110 kV. From the Formula (6), the propagation coefficient between the line supplying the steelworks with a rated voltage of 400 kV and the line supplying the steel plant was determined. The propagation factor is then:

$$TC_{AB} = \frac{S_{SC}(B)}{S_{SC}(A)} = \frac{1512}{8774} = 0.17 \quad (6)$$

With the measurement data of the flicker indicators at the level of 110 kV, the values of the indicators at the level of 400 kV can be determined:

$$P_{st}(A) = P_{st}(B) \times 0.17 \quad (7)$$

Figure 9 shows changes in flicker indicators recorded during one week and determined theoretically with the calculated $TC_{AB} = 0.17$ propagation coefficient.

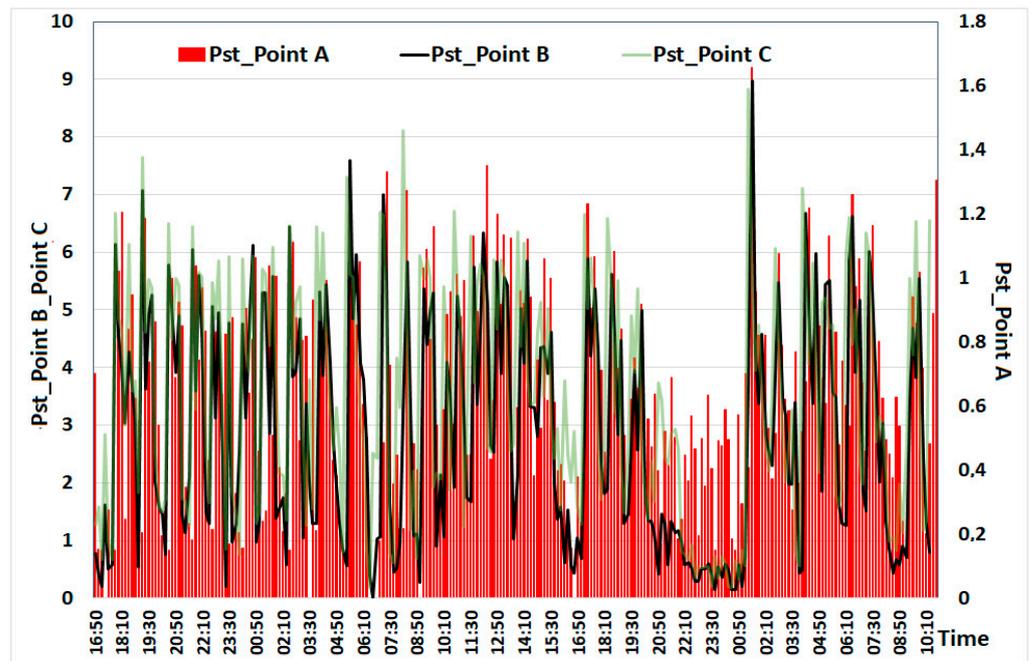


Figure 6. Changes of P_{st} short-term flicker severity recorded simultaneously during one week of measurements at three points: steelworks supply line—point A, EAF supply line—point B, LF supply line—point C.

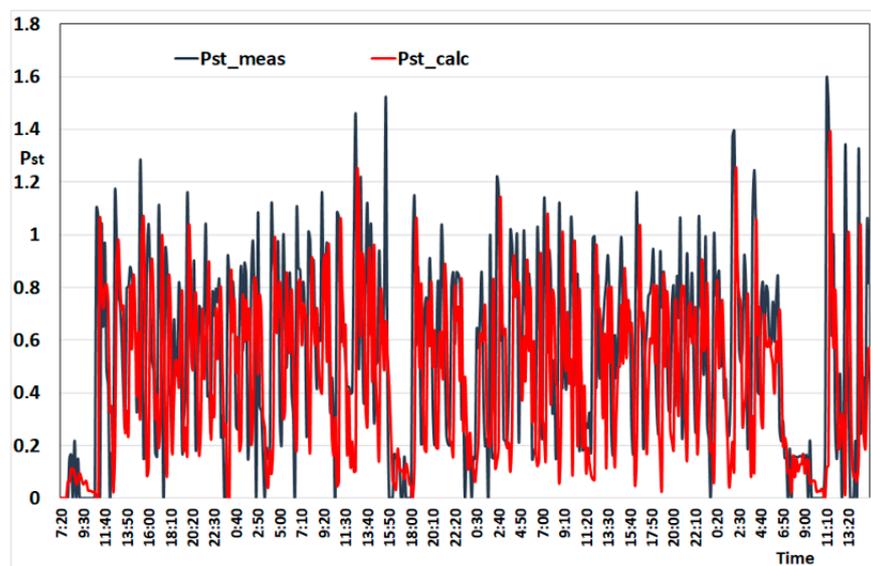


Figure 7. Changes of P_{st} short-term flicker severity recorded during one week of measurement ($P_{st_Point\ A_meas}$) and determined by Formula (5) ($P_{st_Point\ A_cal}$).

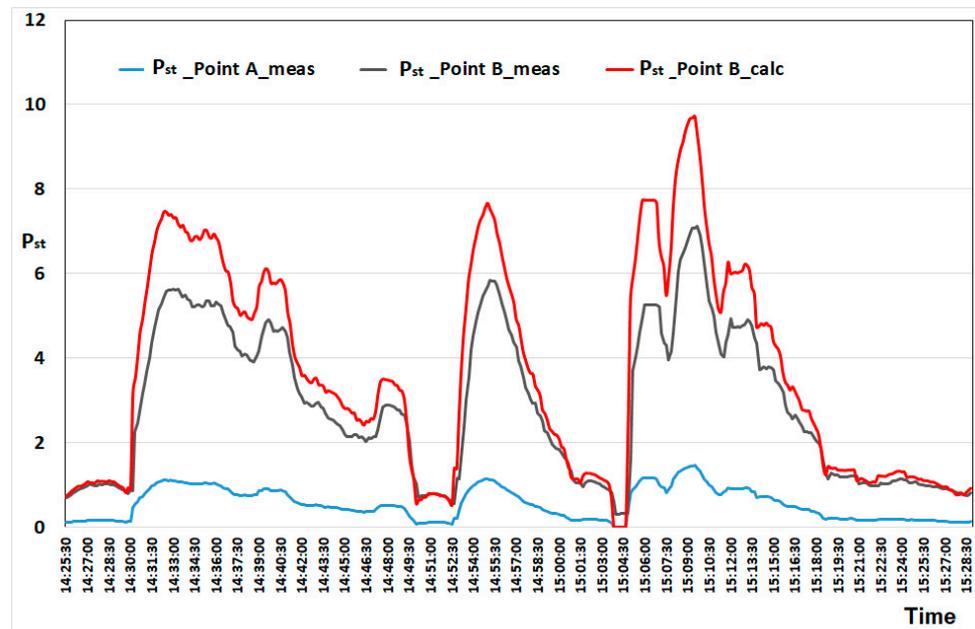


Figure 8. Changes of P_{st} short-term flicker severity recorded simultaneously during one week of measurements at two points: steelworks supply line ($P_{st_Point\ A_meas}$), EAF supply line ($P_{st_Point\ B_meas}$) and determined by the Formula (5) ($P_{st_Point\ B_calc}$).

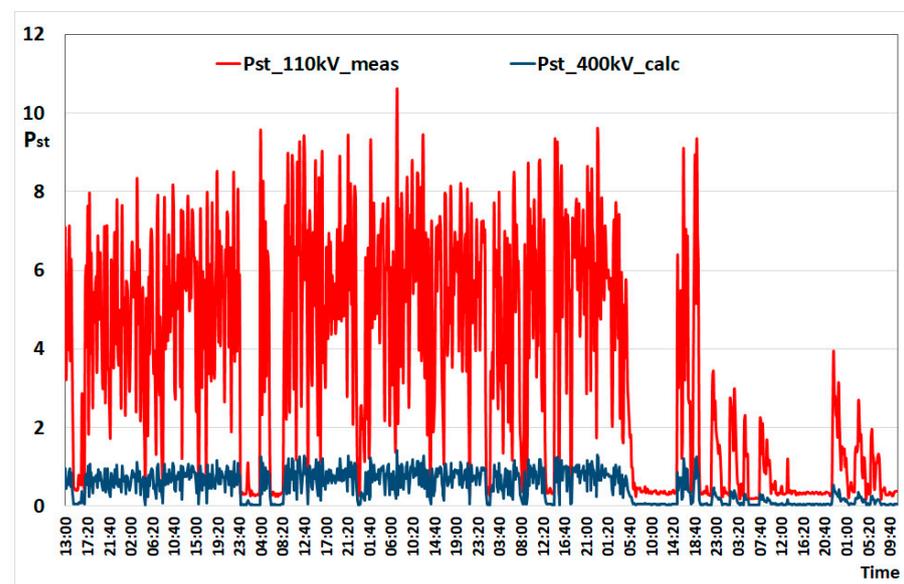


Figure 9. Changes of P_{st} short-term flicker severity recorded during one week of measurement ($P_{st_110\ kV_meas}$) and determined by the Formula (5) ($P_{st_400\ kV_calc}$).

Based on the measurement results, the following attenuation coefficient C values between individual voltages were proposed in [5]:

- from extra high voltage (EHV) networks to high voltage (HV) networks propagation factor equals $C = 0.8$;
- propagation factor from high voltage (HV) networks to medium voltage (MW) networks equals $C = 0.9$;
- from medium voltage (MW) networks to low voltage networks (LV) propagation factor equals $C = 1$.

The above C attenuation coefficient take into account only the influence of the transformer, while the influence of the compensator or series reactor, for example, is neglected.

The publication [40] presents the formula for $P_{st99\%}$ taking into account the above factors:

$$P_{st99\%} = K_{st} \frac{S_{ccf}}{S_{ccr}} \frac{1}{R_{SVC}} \frac{1}{R_{self}} C \quad (8)$$

where

$$R_{SVC} = \frac{P_{st99\%} - \text{with a compensator}}{P_{st99\%} - \text{without compensator}} \quad (9)$$

and

$$R_{SVC} = \frac{P_{st99\%} - \text{with a choke}}{P_{st99\%} - \text{without choke}} \quad (10)$$

Taking into account that the propagation factor C from high-voltage (HV) networks to medium-voltage (MW) networks equals $C = 0.9$, we corrected the theoretically determined course of the flicker $P_{st_Point\ B_calc}$ shown in Figure 8.

Figure 10 compares the theoretical courses of the $P_{st_Point\ B_calc}$ light flicker indices determined on the basis of the Formula (5) and $P_{st_Point\ B_calc_C}$ corrected for the attenuation factor $C = 0.9$.

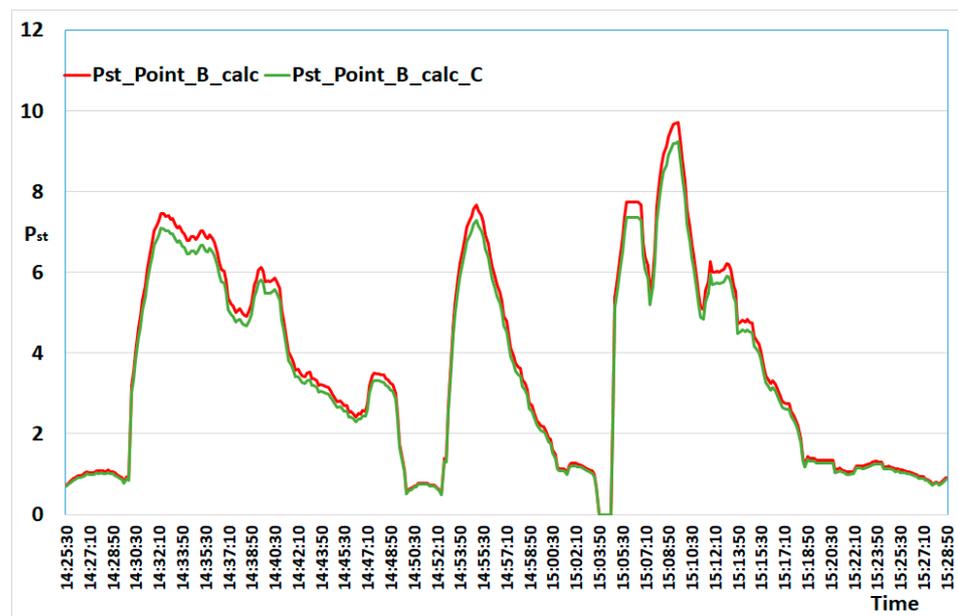


Figure 10. Changes of P_{st} P_{st} short-term flicker severity determined by Formula (5) ($P_{st_Point\ B_calc}$).

In the analyzed supply system arc furnace, voltage fluctuation compensation devices were not installed.

4. Statistical Analysis of Flicker of Light Indicators

Statistical analysis of light flicker indices in networks supplying arc furnaces is presented by the authors of [41]. An analysis was performed for 10-minute measurement intervals of the flicker indicators. Measurement cycles included long measurement periods—one week.

The statistical analysis of changes in short-term flicker severity P_{st} in short time intervals covering individual heats in the arc furnace is presented below. The statistical analysis of the short-term flicker severity P_{st} was based on the data recorded during individual melts (10 s measurement intervals). Figure 11 shows the change of the P_{st} coefficient measured in the three phases of the steelworks supply network during one melt carried out in the arc furnace. Very high values of the flicker coefficient are visible in particular phases, namely, $P_{stmax(L1)} = 9.81$; $P_{stmax(L2)} = 9.60$; $P_{stmax(L3)} = 9.69$. The high-

level flicker of light results from the relatively low short-circuit power $S_{SC} = 750$ MVA in relation to the power at the short circuit of the electrodes with the approximate charge $S_{SCf} = 40$ MVA.

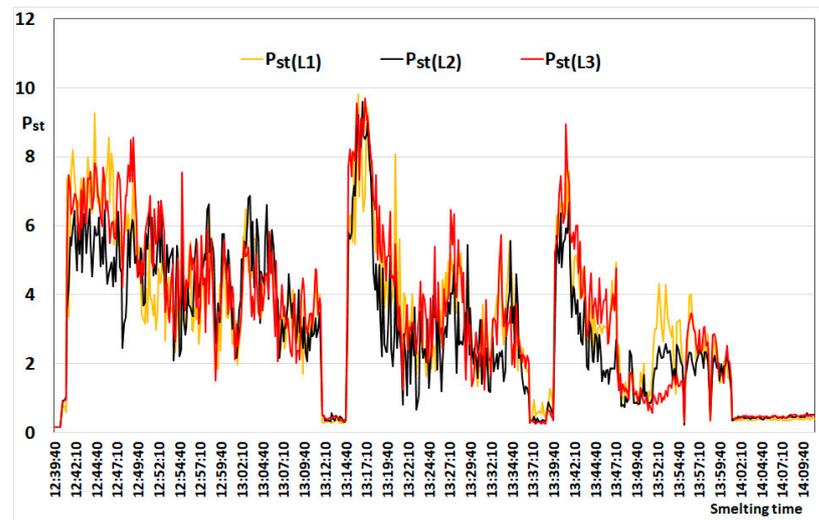


Figure 11. Changes in the short-term flicker severity P_{st} recorded during one melt in the arc furnace.

A short analysis of the obtained measurement results in three phases is presented below. The correlation coefficients between the indicators recorded in individual phases are as follows:

$$r_{P_{st(L1)}P_{st(L2)}} = 0.876r_{P_{st(L1)}P_{st(L3)}} = 0.905r_{P_{st(L2)}P_{st(L3)}} = 0.889 \quad (11)$$

The correlation coefficients between the indicators measured in individual phases and their average values are slightly higher and amount to:

$$r_{P_{st(L1)}P_{stmean}} = 0.963r_{P_{st(L2)}P_{stmean}} = 0.955r_{P_{st(L3)}P_{stmean}} = 0.969 \quad (12)$$

This calculation limited to taking into account the results of measurements in the phase with the greatest voltage fluctuations, as it is adopted by Électricité de France [26].

The conducted analysis reveals that in the case of the disturbing influence of the electric arc furnaces, it is correct to take both average values and those measured in one of the line phases—the phase with the highest P_{st} . As it results from the measurements carried out by the authors, with the asymmetry coefficient below the permissible value, light flicker indicators in all phases change within a similar range.

Table 1 shows the basic statistical parameters of the short-term flicker severity P_{st} measured during one melt in the arc furnace.

Table 1. Statistical parameters of the short-term flicker severity P_{st} measured during one melt in the arc furnace.

Class Number	Class Range	Center Class	Amount	Periodicity	Cumulative Amount	Cumulative Periodicity
I	P_{st}	P_{st}	n_i	f_i	n_i^*	f_i^*
1	0.15–1.12	0.635	52	0.107	52	0.107
2	1.13–2.09	1.61	58	0.119	110	0.226
3	2.10–3.06	2.58	94	0.193	204	0.420
4	3.07–4.03	3.55	103	0.212	307	0.632
5	4.04–5.00	4.52	64	0.132	371	0.763
6	5.01–5.97	5.49	47	0.097	418	0.860
7	5.98–6.94	6.46	37	0.076	455	0.936
8	6.95–7.91	7.43	18	0.037	473	0.973
9	7.92–8.88	8.4	8	0.016	481	0.990
10	8.89–9.85	8.92	5	0.010	486	1.000

As in the case of voltage fluctuations, the basic statistical parameters of the recorded sample (L1 phase—with the highest P_{st}) during one melt (10 s sampling periods) were determined for the flicker index. In the first stage, grouping was performed, i.e., the classification of the measured light flicker indices by dividing the sample into classes. For the measured short-term flicker severity during one smelting, the number of samples is $n = 443$. The number of class intervals per $m = 10$ was established with the length of the class interval being 0.97.

Figure 12 shows a graph of the distribution of the obtained samples of short-term flicker severity, approximated by the function characterizing the normal distribution with the same mean and standard deviation.

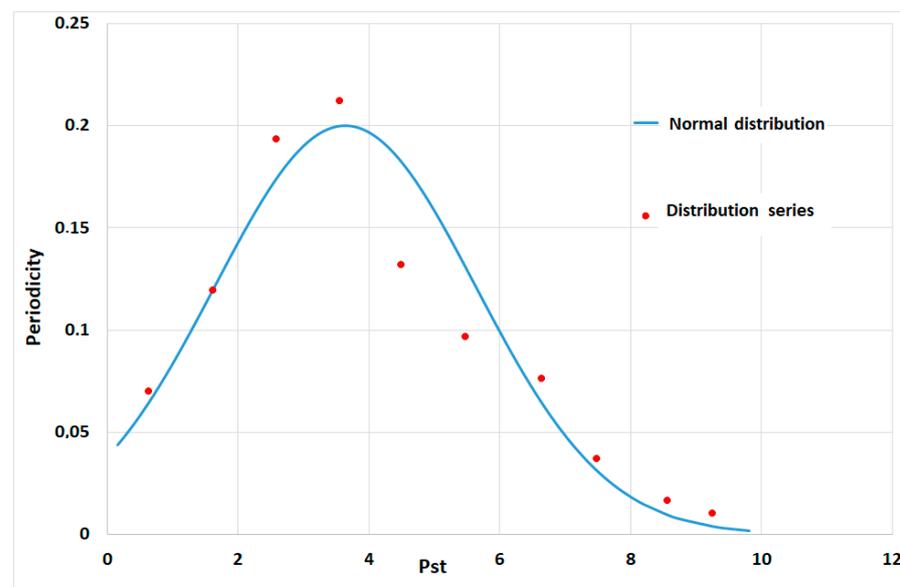


Figure 12. Distribution of the probability density function of short-term flicker severity: theoretical and real.

In order to determine the nature of changes in the short-term flicker severity during several successive heats when operating a single furnace, one day of light flicker measurements (selected from a measurement campaign covering one week) was taken into account. The measurement was made in accordance with EN—50160 [32] with 10-minute periods of determining the short-term flicker severity P_{st} . During one day of measurements, the obtained 144 values of the flicker index varied from $P_{stmin} = 0.25$ with the arc furnace off, to $P_{stmax} = 7.69$ with the furnace operating in the melting phase. The mean value of the short-term flicker severity was $P_{stmax} = 3.94$. and its standard deviation $D(P_{st}) = 1.69$. As in the case of the amplitudes of voltage fluctuations and the flicker index of light measured for one smelt, as well as for one-day measurement, the basic statistical parameters of the distribution series created earlier from the measured values were calculated; they are listed in Table 2.

Table 2. Statistical parameters of the short-term flicker severity P_{st} measured in one day.

Class Number	Class Range	Center Class	Amount	Periodicity	Cumulative Amount	Cumulative Periodicity
i	P_{st}	P_{st}	n_i	f_i	n_i^*	f_i^*
1	0.25–1.31	0.780	8	0.0556	8	0.0556
2	1.32–2.37	1.845	20	0.1389	28	0.1944
3	2.38–3.43	2.905	30	0.2083	58	0.4028
4	3.44–4.49	3.965	30	0.2083	88	0.6111
5	4.50–5.55	5.025	28	0.1944	116	0.8056
6	5.56–6.61	6.085	20	0.1389	136	0.9444
7	6.62–7.67	7.145	8	0.0556	144	1.0000

The distribution series was divided into $m = 7$ classes with the class length calculated as $(P_{stmax} - P_{stmin})/m = (7.69 - 0.25)/7 = 1.06$.

Figure 13 shows the probability density function for one day of measurements of the short-term severity flicker P_{st} .

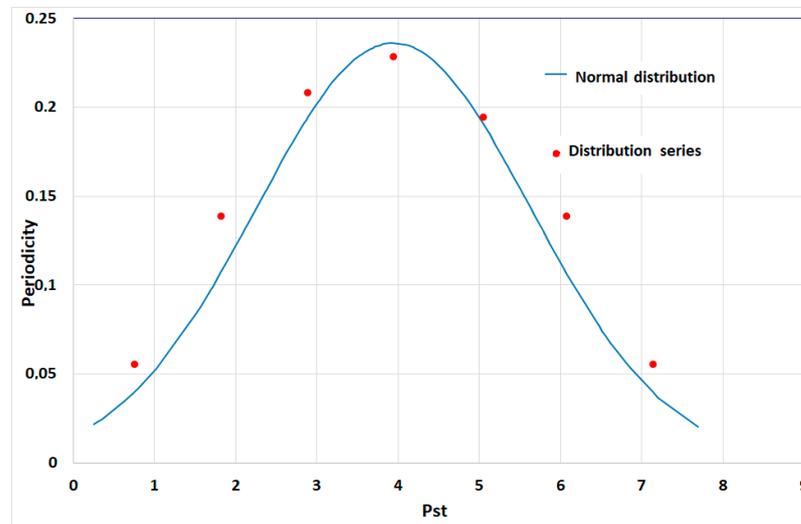


Figure 13. Probability density function for one day of measurements of the short-term severity flicker P_{st} .

To verify the validity of the hypothesis with a normal distribution, the χ^2 Pearson compatibility test was performed at the significance level of 0.05.

Table 3 contains the basic parameters calculated for a given sample ($n = 144$) with the mean value $P_{stmean} = 3.94$ and the standard deviation $D(P_{st}) = 1.69$.

Table 3. Statistical data for the χ^2 Pearson test.

P_{sti}	n_i	z_i	$F(z_i)$	p_i	np_i	$(n_i - np_i)^2/np_i$
1.31	8	-1.56	0.0594	0.06	8.55	0.0358
2.37	20	-0.93	0.1762	0.12	16.82	0.6015
3.43	30	-0.30	0.3821	0.21	29.65	0.0041
4.49	30	0.32	0.6255	0.24	35.05	0.7275
5.55	28	0.95	0.8289	0.20	29.29	0.0568
6.61	20	1.58	0.9429	0.11	16.42	0.7825
7.67	8	2.21	0.9864	0.06	8.55	0.0358
Sum	144	x	x	1.00	144	2.2441

The critical value read from chi-squared tables for the adopted significance level $\alpha = 0.05$ and 4 degrees of freedom is $\chi_{\alpha}^2 = 9.49$ and since the value determined from the sample is $\chi^2 = 2.24 < \chi_{\alpha}^2 = 9.49$, there is no reason to reject the hypothesis that the analyzed distribution is a normal distribution.

5. Assessment of The Increase in Flicker of Light with Parallel Operation of Arc Devices

The increase in voltage fluctuations resulting from successively connected arc devices is characterized by the K_N coefficient. This factor determines the extent to which voltage fluctuations will increase with successively connected arc furnaces in relation to the fluctuations generated during the operation of a single device.

For the value of the short-term flicker index, K_N can be determined from the formula [26]:

$$K_N = \frac{P_{stN}}{P_{st1}} \quad (13)$$

According to the method proposed by UIE for the assessment of superposition of voltage fluctuations, the substitute parameter P_{st} obtained with the use of the light flicker meter is assumed, and it is determined from the relationship [42].

$$P_{st} = \sqrt[m]{P_{st1}^m + P_{st2}^m + \dots + P_{stn}^m} \quad (14)$$

P_{stn} corresponds to flicker level induced by the n -th disrupting receiver. The value of the coefficient m , occurring in the above formula, depends upon the characteristics of unquiet receivers, and can be categorized into five categories:

$m = 4$ —used only for the summation of voltage changes due to arc furnaces specifically run to avoid coincident melts;

$m = 3.2$ —this choice matches the slope of the straight part of the $P_{st} = 1$ curve;

$m = 3$ —this is used for most types of voltage changes where the risk of coincidental voltage occurring is small. The vast majority of studies combining unrelated disturbances will fall into this category, and it should be used where there is any doubt over the magnitude of the risk of coincident voltage changes occurring;

$m = 2$ —this is used where coincident stochastic noise is likely to occur, e.g., coincidental melts on arc furnaces;

$m = 1$ —the resultant P_{st} will approach the value given by this coefficient when there are very high occurrences of coincidental voltage changes.

In the method recommended by UIE, it is proposed to determine the increase in the flicker index caused by successively connected arc devices by changing the m factor in Formula (14) from 2 to 4.

An attempt to explain the reasons for the discrepancies in the assessment of voltage fluctuations occurring with the simultaneous operation of several furnaces, created by various methods, was made in Poland by Wąsowski [43,44].

The K_N coefficient was determined from the formula:

$$K_N = \sqrt{N - 4.4N(N - 1) \frac{Q_1}{S_{SC}}} \quad (15)$$

The continuation of the research conducted by A. Wąsowski was presented in publications [13,14,45].

Based on the recorded waveforms of the voltage curve (oscillograms) in the network supplying the lighting receivers of the steelworks (Figure 3—Point D), the RMS voltage values were determined (for the period of 20 ms)—Figure 14.

In relation to the voltage value, with the arc devices off, the switching on the arc furnace causes a decrease in the average RMS voltage value. Switching on other arc furnaces reduces the RMS voltage value. This is due to an increase in voltage drop across the power line impedances.

Along with the decrease in RMS voltage, the switching on of arc furnaces causes voltage fluctuations. The amplitude of the voltage fluctuations increases with the number of switched on arc furnaces—Figure 15.

The effect of an increase in voltage fluctuations is an increase in flicker. Based on the analysis of the recorded voltage fluctuations and flicker of light indicators, the correlation between these values was determined. Figure 16a shows the changes in the amplitude of voltage fluctuations and the flicker index recorded during one melting in the arc furnace. A correlation was also established between these values (Figure 16b). The correlation coefficient is $r_{P_{st}\Delta U} = 0.906$.

Taking into account changes in the mean RMS voltage when switching on successive arc devices and developed power–voltage characteristics, the set of formulae allowing the determination of the coefficient K_N was worked out [45].

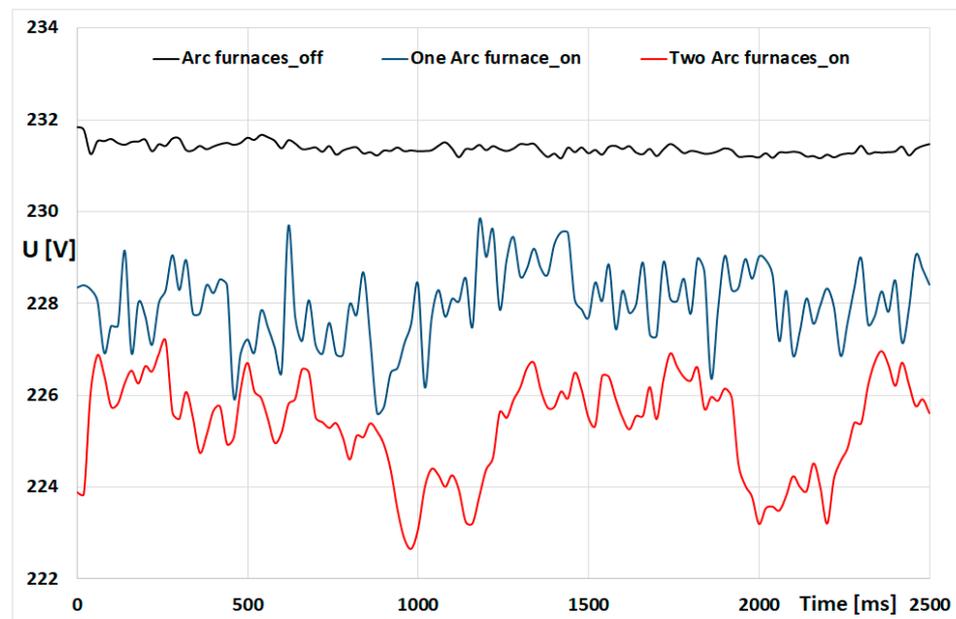


Figure 14. Changes in RMS voltage with arc furnaces off, one and two furnaces on.

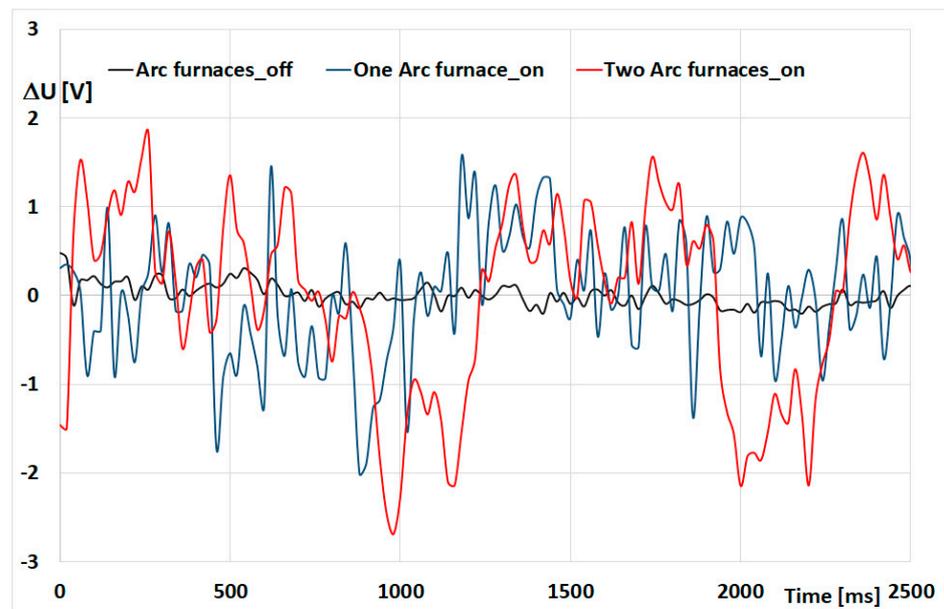


Figure 15. Changes in voltage fluctuations (ΔU) with arc furnaces off, one and two furnaces on.

The formula determining an increase in voltage fluctuations for arc devices in the melting process can be expressed in the following form:

$$K_N = \frac{\sqrt{N}}{\sqrt{1 + \frac{(N-1)k_q Q_1}{S_{SC}} \left(\frac{U_{SN}}{U_{S1}}\right)^2}} \quad (16)$$

and for arc devices of different power,

$$K_N = \frac{\sqrt{\sum_{i=1}^{Nr} \left(\frac{S_{ni}}{S_{n1}}\right)^2}}{\sqrt{1 + \sum_{j=2}^N \left(\frac{k_q Q_j}{S_{SC}}\right) \left(\frac{U_{SN}}{U_{S1}}\right)^2}} \quad (17)$$

Using the relationship determined for power–voltage characteristics, and replacing the arc by the voltage source in Formulas (16) and (17) at identical devices, we can present the coefficient K_N in the following form:

$$K_N = \frac{\sqrt{N}}{\sqrt{1 + \frac{(N-1)k_q^* S_{SCf1}}{S_{SC}} \left(\frac{U_{SN}}{U_{S1}}\right)^2}} \tag{18}$$

and at different devices,

$$K_N = \frac{\sqrt{\sum_{i=1}^{Nr} \left(\frac{S_{ni}}{S_{n1}}\right)^2}}{\sqrt{1 + \sum_{j=2}^N \left(\frac{k_q^* S_{SCfj}}{S_{SC}}\right) \left(\frac{U_{SN}}{U_{S1}}\right)^2}} \tag{19}$$

In the method recommended by UIE, an increase of flicker caused by consecutive connecting arc devices is determined by the change of the coefficient m from value of 2 to 4 in Formula (14). For identical furnaces causing identical flicker ($P_{st1} = P_{st2} = \dots = P_{stn}$), Formula (14) can be transformed to the form:

$$P_{st} = \sqrt[m]{P_{st1}^m + P_{st2}^m + \dots + P_{stn}^m} = \sqrt[m]{N \cdot P_{st1}^m} = \sqrt[m]{N} P_{st1} \tag{20}$$

At bordering values $m = 2$ and $m = 4$ recommended by UIE, this leads to the formula for K_N :

$$K_N = \sqrt{N} \text{ and } K_N = \sqrt[4]{N} \tag{21}$$

Figure 17 shows the changes in the K_N coefficient depending on the number of parallel arc furnaces. The curves drawn on the basis of Formula (20) recommended by UIE are marked in red.

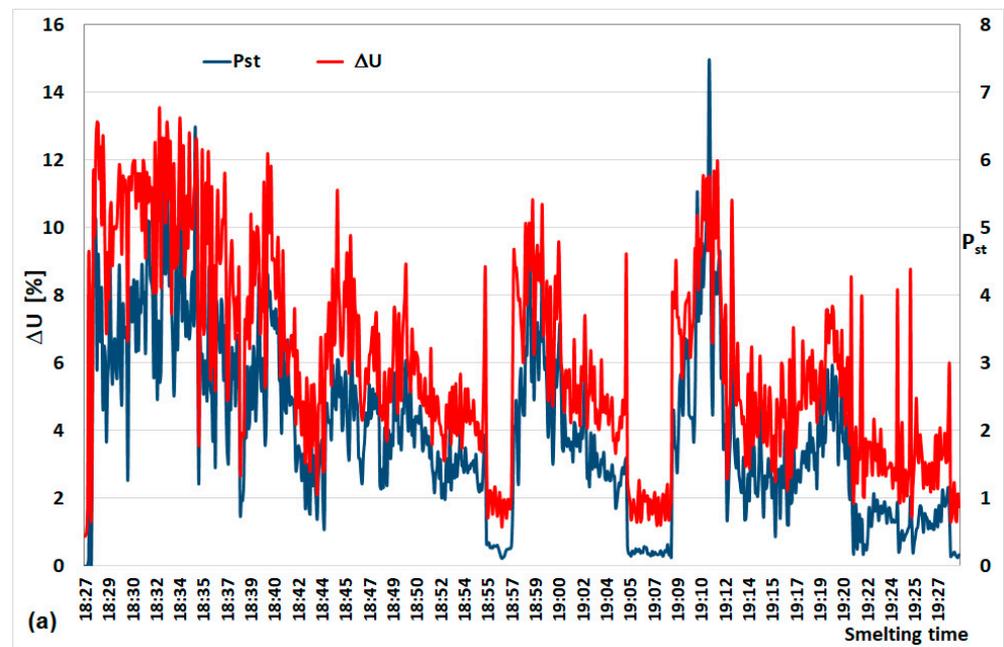


Figure 16. Cont.

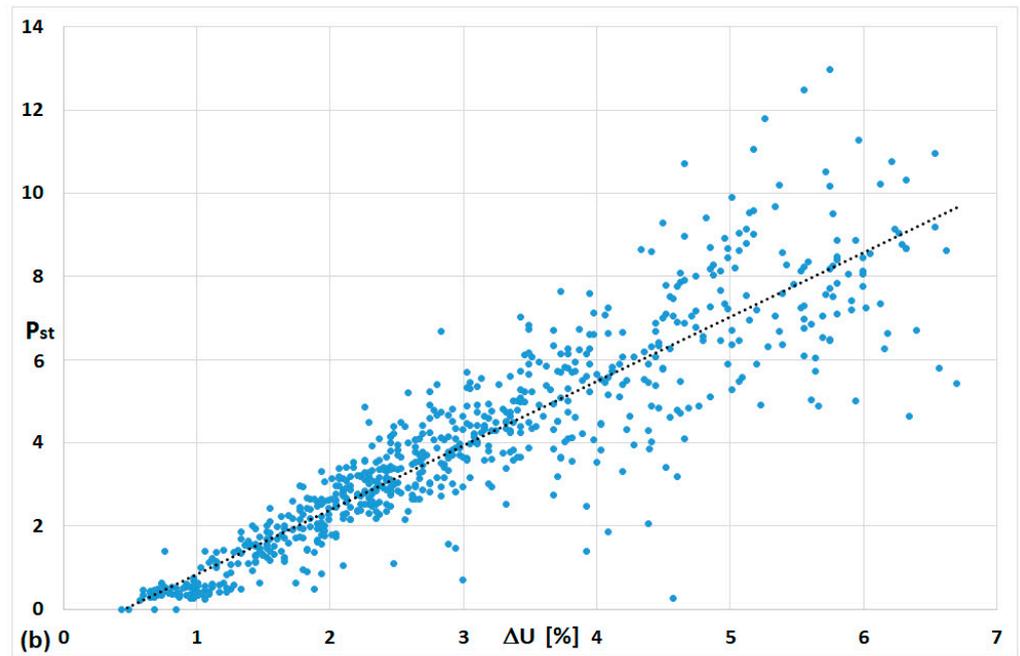


Figure 16. Changes of short-term severity flicker P_{st} , voltage fluctuations ΔU (a) measured during one melt and correlation between P_{st} — ΔU (b).

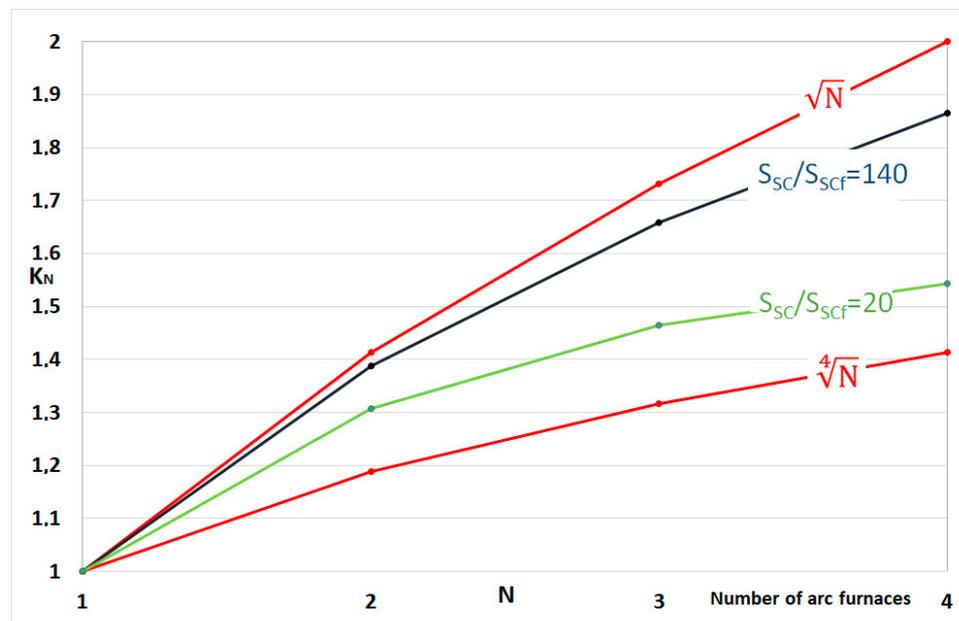


Figure 17. Changes in coefficient K_N according to the number of parallel operating arc furnaces in steel plant.

Based on the proposed Formulae (16)–(19), the values of the K_N coefficient can be determined depending on the short-circuit power of the S_{SC} network, the power of the transformer at the short-circuit of the electrodes with the charge S_{SCf} , and the voltage in the line supplying the steel plant: respectively for the operation of the N furnaces and the operation of a single furnace (furnace with the highest power, reference furnace). Figure 17 also shows the values of the K_N coefficient corresponding to the supply conditions of the steel plant, the supply scheme of which is shown in Figure 3. For point A, the ratio is $S_{SC}/S_{SCf} = 140$, and for point B it is $S_{SC}/S_{SCf} = 20$.

The analysis shows that the value of the K_N coefficient is decisively influenced by the short-circuit power on the rails of the steel plant. The higher the short-circuit power, the greater the K_N coefficient, i.e., the arc devices interact to a lesser extent, mitigating the increase in voltage fluctuations. Obviously, the voltage fluctuations and flicker of light at $S_{SC}/S_{SCf} = 20$ are greater than at $S_{SC}/S_{SCf} = 140$.

6. Discussion

The main disturbances generated by arc devices are voltage fluctuations. Voltage fluctuations caused by arc furnaces are characterized by high dynamics of change. The value of the voltage fluctuations depends mainly on the melting phase in the arc furnace and on the short-circuit power of the network in relation to the power of the arc furnace transformer. The periodicity of voltage fluctuations (number of changes during a given time, e.g., a second) changes to a lesser extent.

One of the effects of voltage fluctuations is flicker of light generated by lighting receivers. The flicker annoyance is assessed on the basis of the analysis of the values of the flicker P_{st} and P_{lt} indicators. The volume measured by the flickermeter (or the power quality parameter analyzer with the flicker index function) is the voltage change. The remaining elements (functions) must be modeled: the reaction of the lamp–eye–brain system. A 60 W bulb was adopted as the reference lamp. With the currently widely used LED lamps, this assumption is debatable. It is therefore appropriate to ask the question: should the algorithm be modified for determining the flicker indicators by introducing a new reference lamp? According to the authors, this may create a problem related to the use of existing flickermeters and the need for further modifications when developing new light sources.

It seems a more reasonable solution to increase the permissible value of the light flicker coefficient depending on the light sources used. Another suggestion is to adopt $P_{lt} < 1$ for a different registration period, for example, 80% of the time instead of 95% currently used.

Commission Regulation (EU) 2019/2020 of 1 October 2019 lays down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament proposing flicker $P_{stLM} \leq 1$ for LED and OLED MLS. The determined value shall not exceed the declared value by more than 10%. Adopting a new P_{stLM} unit requires the use of specialized photometric equipment that also allows SVM to be measured (stroboscopic visibility measure), as defined in standards $SVM = 1$, represents the visibility threshold for an average observer. The metric for flicker used in this Regulation is the parameter ‘ P_{stLM} ’, where ‘st’ stands for short-term and ‘LM’ for light flickermeter method, as defined in the standards. A value of $P_{stLM} = 1$ means that the average observer has a 50% probability of detecting flicker. Measurements are made in a photometric darkroom by placing the meter at a specified distance from the light source. Another method is to use a meter circuit with an integrating ball, which allows the verification of the ripple characteristics when measuring the luminous flux. The measurements proposed by the EU in [46] are designed to test the resistance of light sources to voltage fluctuations. Before obtaining the certificate, individual types of light sources are tested. This means that the P_{stLM} indicator is completely different from the P_{st} and P_{lt} indicators. P_{st} and P_{lt} relate directly to supply voltage fluctuations that directly affect the flickering of light. P_{stLM} is therefore an additional parameter that is taken into account by manufacturers of LED light sources.

The publication in [47] presents a digital flicker detection method based on probability resampling. Uniform probability distribution sampling is applied before statistical evaluation to compress redundant data to reduce storage space and to improve algorithm execution efficiency. The proposed method based on probability resampling overcomes the shortcomings of the low efficiency of algorithms and the high requirements of hardware resources brought by the traditional flicker digital measurement, which has excellent economic significance and practical impact for both new developments of digital flicker detection instruments and upgrades of traditional power quality instruments [47]. The

presented method of digital analysis of signal detection used to determine light flicker indicators allows faster detection of electricity quality parameters in modern analyzers. This may be of particular importance when modifying the flicker meter to include new light sources (e.g., LED lamps).

The article presents selected examples (representative) flicker of light indicators recorded in the lines supplying arc furnaces. Two methods of light flicker evaluation were adopted. The first one, according to [32–34], consists of the weekly measurement of the parameters characterizing the power quality and relating them to the permissible values.

Figure 18 shows the changes of long-term severity flicker P_{It} and short-term severity flicker P_{st} recorded in the supply line to the ironworks (a)—Point A (Figure 3) and steel plant (b)—Point B (Figure 3), during the weekly measurement cycle.

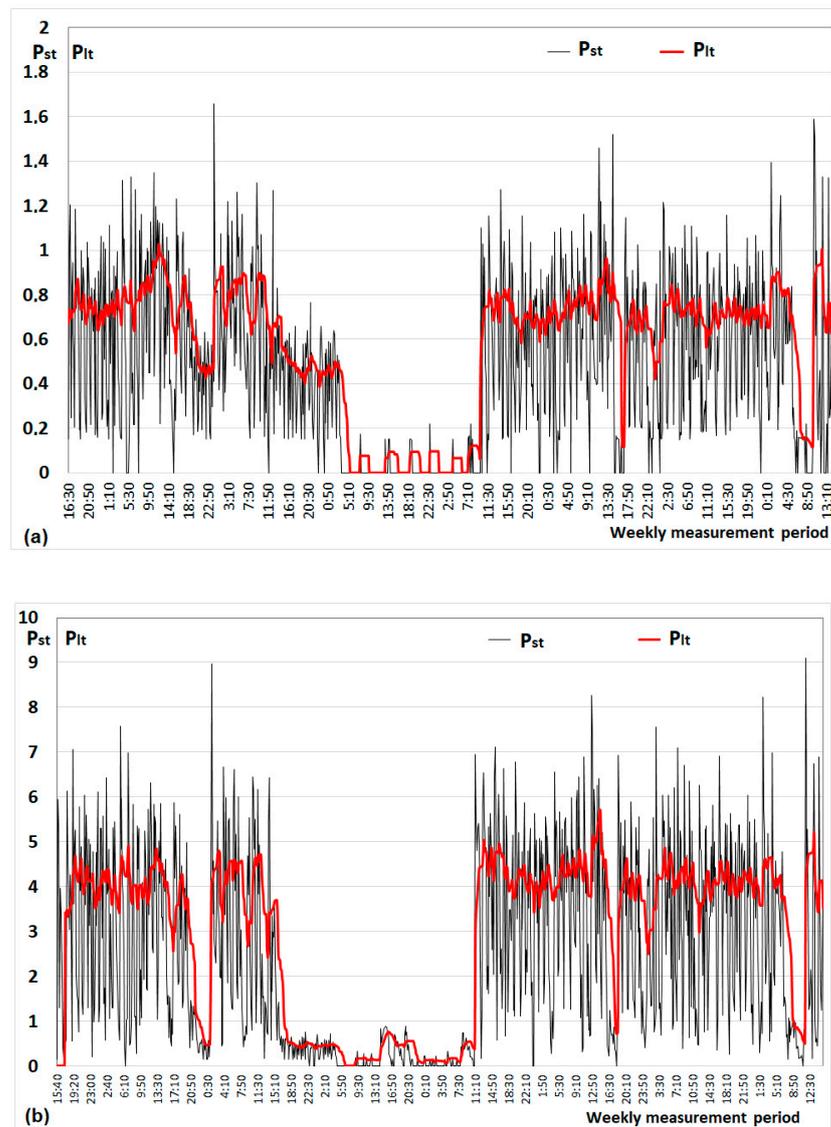


Figure 18. Changes of long-term severity flicker P_{It} and short-term severity flicker P_{st} measured during one week in the supply line to the ironworks (a) and steel plant (b).

Assuming for the 110 kV line, in accordance with the EN 50160 standard [32], the limit value of $P_{It95\%} \leq 0.8$, it was found that the acceptable value was exceeded, although to a small extent. For point A, $P_{It95\%} = 0.89$, $P_{Itmax} = 1.03$. During several weekly measuring cycles at point A, similar $P_{It95\%}$ values were obtained. The values of $P_{It95\%}$ varied from 0.76 through 0.81 to 0.89 (referring to the phase with the highest P_{It} val-

ues). At point A (U_n -110 kV), the short-circuit power of the network is $S_{SC} = 5000$ MVA. The rated power of the furnace transformer is $S_n = 20$ MVA. Assuming the operational short-circuit factor $k_{sc} = 2$, the ratio of the short-circuit power of the network to the power of the furnace transformer at the short-circuit of the electrodes with the charge is $S_{SC}/S_{SCT} = S_{SC}/(k_{SC}S_n) = 5000/40 = 125$.

The publication in [48] proposes the minimum value of $S_{SC}/S_{SCT} = 80$ and in the publication in [49], $S_{SC}/S_{SCT} = 120$. On the basis of the conducted research, the authors concluded that the minimum ratio of the short-circuit power of the network to the short-circuit power of the electrodes with the charge should be greater than 125.

The use of short measurement intervals (a few seconds) allows the assessment of disturbances caused by the arc furnace during individual melts. On the basis of the performed statistical analysis, a significant correlation of changes in the flicker coefficients of light in individual phases of the lines feeding the arc furnaces was found—Formulae (11) and (12). Therefore, the P_{st} and P_{lt} analysis was proposed in the phase in which the highest values were recorded. Comparing the conducted statistical analysis of the P_{st} light flicker indices recorded at 10 s (one melt) and 10 min (one day of measurements) measurement intervals, a very similar probability density function was found—Figures 12 and 13.

7. Summary

Arc furnaces, being one of the largest receivers connected to the electrical system, generate a number of disturbances affecting the quality of electricity. Voltage fluctuations are among the major disturbances and the flicker phenomenon presented in the article is the effect of these fluctuations. Measuring the flicker with power quality analyzers appears to be the best method of assessing flicker levels. In the case of dynamically changing power consumed by arc furnaces, it is advisable to shorten the measurement intervals. This allows for a detailed analysis of disturbances during individual stages of the arc furnace smelting. The proposed method of determining the K_N coefficient defining the increase in light flickering with arc furnaces operating in parallel in a steel mill, compared to the method recommended by UIE (Formula (14)), takes into account, among others: different powers of individual furnace transformers, supply conditions of the steel mill represented by short-circuit power, voltage reduction in supply network at successively connected electric arc furnaces and the individual smelting phases in the electric arc furnace. Assuming that the frequency of voltage fluctuations generated by arc furnaces changes within a small range from a few to several changes per second, it was found that the proposed K_N factor determines both the degree of increase in voltage fluctuations and light flicker in the parallel operation of arc furnaces.

Author Contributions: Conceptualization, Z.O.; methodology, Z.O., Z.Ł.; software, Z.O.; validation, Z.O., Z.Ł.; formal analysis, Z.O., Z.Ł.; investigation, Z.O.; resources, Z.O.; data curation, Z.O.; writing—original draft preparation, Z.O.; writing—review and editing, Z.O.; visualization, Z.O.; supervision, Z.Ł.; project administration, Z.Ł.; funding acquisition, Z.Ł. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following nomenclatures are used in this manuscript:

P_{lt}	long-term flicker severity
P_{st}	short-term flicker severity
TC_{AB}	transfer coefficient
C	coefficient of propagation (attenuation coefficient)
R_{SVC}	factor that limits voltage fluctuations through the compensator
R_{self}	coefficient limiting voltage fluctuations through the choke
K_N	coefficient determining the increase in flicker of light depending on the number of parallel operating arc furnaces in steel plant
P_{stN}	value of the short-term light flicker indicator recorded during the operation N of arc furnaces
P_{st1}	value of the short-term light flicker indicator recorded during the operation of a single arc furnace
N	number of parallel operating arc furnaces in steel plant
S_{scf}	short-circuit power capacity when shorting the electrodes with the scrap
S_{sc}	short-circuit power capacity of the network
n_i^*	cumulative amount
f_i^*	cumulative periodicity
S_{ntr}	power of the furnace transformer
U_N	rated voltage
ΔU	voltage fluctuations
k_q^{\bullet}, k_q^*	slope coefficients of the power–voltage characteristic calculated at a constant arc voltage and a constant arc resistance, respectively
\bar{Q}_j	mean reactive power drawn by j-th furnace
$U_{SN}; U_{S1}$	voltage on the bus-bars of the steelwork at the work of N furnaces and the work of a single furnace (the furnace of the highest power, reference furnace), respectively
K_{st}	coefficient characterizing the emission of fluctuations of the considered furnace, ranging between 48 and 85 with an average value of approx. 60 (K_{st} changes with the change of the probability function of not exceeding P_{st})
C	attenuation coefficient between individual voltage levels
R_{SVC}	a factor that limits voltage fluctuations through the compensator
R_{self}	coefficient limiting voltage fluctuations through the choke

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