ELECTRIC ARC FURNACE IN POWER SYSTEM. ASPECTS OF POWER QUALITY. A CASE STUDY

Ljubomir Nikoloski, Goran Rafajlovski* Faculty of Electrical Engineering, Skopje, Republic of Macedonia
*Electric Power Company of Macedonia

Abstract: *The aspects of power quality in PCC where an arc furnace for steel melting with alternating current is connected. By measurements of flicker, harmonics content in voltage and current, the preservation of the reference levels for the supply voltage and emission limits for the furnace as a customer are evaluated. In that way the unambiguous evaluation of the power quality aspects in light of contemporary standards is given.*

key words: Harmonics, Flicker, Arc Furnace

1. INTRODUCTION

An arc furnace of 40 MVA for steel melting is connected in the 110 kV voltage level in the Power System of Republic of Macedonia. With the help of the measurements of some power quality quantities we try to check the reference levels in the point of common coupling (PCC) and the emission limits of the arc furnace as a consumer. The measured quantities are voltage and current harmonics and flicker.

The measurements should also answer the question if the power of this furnace could be increased without additional technical improvements, or in other wording, if the power system has a capacity for more emission of disturbances.

2. DESCRIPTION OF THE POWER SYSTEM AND PCC

The power system connections in the region of town Skopje is given on fig. 1

The substation "Sever" where the whole steelworks "Zelezara" is fed is connected to the substation "Skopje 1". In that manner, PCC for the whole factory is the substation "Skopje 1", but for the arc furnace alone, the PCC is in substation "Sever", fig. 2.

Power quality disturbances are many and they are defined in standards and recommendations. The principles of regulations of relations between utility and consumers are so arranged, that the utility is responsible for **reference levels** for the power quality factors, mainly for the voltage at the PCC. The customers are responsible for the **emission limits** of the power quality factors.

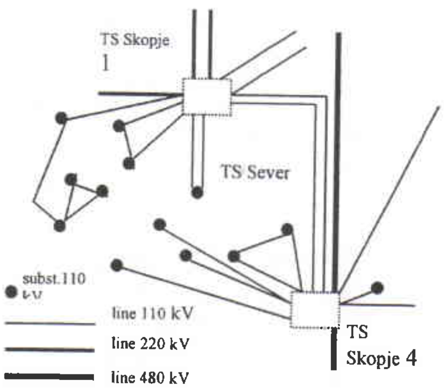

fig. 1. *Power connections in the region of town Skopje*

Today, power quality factors are defined as statistical quantities. A 95% level for THD U means that this level is not passed in 95% of the time in a test period. The test period for measurements commonly accepted is one week.

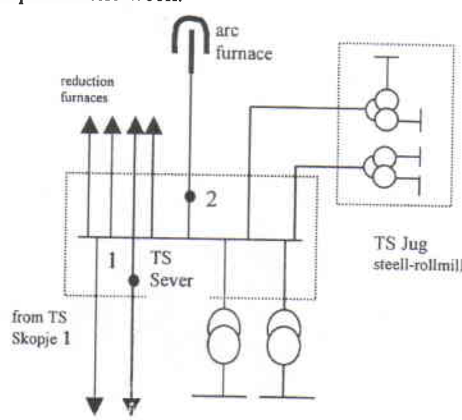

fig. 2. *Diagram of electrical connections of the main consumers in steel factory "Zelezara"*

As could be seen from fig. 1 and 2, the PCC of this arc furnace is not optimal from the point of view of power quality. First of all, in the town of Skopje and its close vicinity there is no power production plant. They are as far as 80 to 150 km from the town. And also, the highest voltage transmission line of 380 kV which is build later, is connected to substation "Skopje

4" first and then to "Skopje 1" only with the 110 kV connection. According to a study made in 1984 the short circuit power at the substation Skopje 1 on 110 kV level is S_{sc}= 4380 MVA.

As is seen from fig. 2 the two points where the measurements were made are: point 1, in the one of the feeders at 110 kV level, and point 2, where the arc furnace is fed. The power consumption of the steel factory when the measurements were made (October 1998) was on very low level.

All 5 reduction iron melting electric furnaces were out of work, but only the arc furnace and steel rolling mill were in work. They were the main disturbances emitters in the power grid. So the results of the measurements and evaluations of power quality are valid for this situation only.

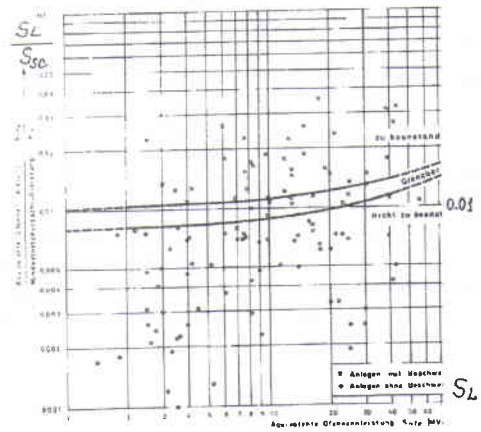

fig. 3 *Relation between furnace power* S_L *and the ratio* S_L / S_{sc}

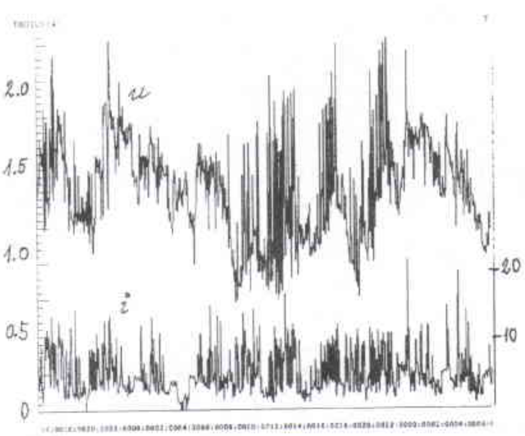

fig. 4 *Time dependence for THD U and THD I*

3. STANDARDS AND RECOMMENDATIONS

Voltage harmonics. Concerning high voltage grids (level 110 kV) the norms and recommendations are slightly different. The norms of Austria, France, UK and USA allow 1,5% for THD U; Japan, Sweden and others allow 1%, Russia 2% and South Africa 3%.

One recently accepted national standard [2] is from Argentina, the organization ENRE. There it is prescribed as a reference level THD U = 3% for high voltage grids and for harmonics the values from table 1.

Table 1: *Reference levels for voltage harmonics according to ENRE (Argentina) [3]*

ord. i	5	7	11	13	17	19	23	25
U_i %	2	2	1.5	1.5	1.0	1.0	0.7	0.7
ord. i	3	9	15	21	>21			
U_i %	1.5	1.0	0.3	0.2	0.2			
ord. i	2	4	6	8	10	12	>12	
U_i %	1.3	1.0	0.5	0.2	0.2	0.2	0.2	

Flicker. German recommendations VDEW [2] prescribe the reference level for flicker in high voltage grids: A_{lt} = 0.2 or A_{st} = 0.5. The emission limit for flicker caused by one customer alone is set A_{lt} = 0,02 or A_{st} = 0.2.

The emission limit for flicker according to ENRE [2] is dependent of the short circuit power of the system at PCC and the power of the consumer, according to the formula:

$$A_{st} = 0.5 \cdot \frac{\frac{S_L}{S_{sc}}}{x} \left\{ \begin{array}{ll} x = 20, & \frac{S_{sc}}{S_L} \le 100 \\ x = 20 \ldots 100 & \frac{S_{sc}}{S_L} = 100 \ldots 1000 \end{array} \right\}$$

Here S_L is the power of the consumer, S_{SC} is the short circuit power of the system in the PCC. For our case it is S_L = 40 MVA, S_{SC} = 4380, and with x = 22, A_{st} = 01.

Current harmonics. According to ENRE [2] for a customer like this the emission limits for current harmonics are given in table 2

Table 2: *Emission limits for current harmonics according to [2]*

i	5	7	11	13	17	19	23	25	>25
I_i %	6.0	5.1	2.9	2.2	1.8	1.7	1.1	1.1	0.4
i	3	9	15	21	>21				
I_i %	7.5	2.2	0.8	0.4	0.4				
i	2	4	6	8	10	12	>12		
I_i %	10.0	3.3	1.5	0.5	0.5	0.5	0.5		

According to IEEE 519 [4] the current harmonics for high voltage transmission grids.are given in table 3 and they are emission limits. They depend on I_{sc}/I_L ratio. The even harmonics are limited to 25% of those values. For our case the third row is appropriate.

IEEE 519 also gives typical values for current harmonics of an arc furnace, table 4

VDEW recommendation gives also an equation for flicker prediction of the arc furnace without measurement:

Table 3 *Emission limits for current harmonics (IEEE)*

I_{SC}/I_t	<11	11≤h<17	17≤h<23	23≤h<35	h>35	THDI
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	**6.0**	**2.75**	**2.5**	**1.0**	**0.5**	**7.5**
>1000	7.5	3.5	3.0	1.25	0.7	10

Table 4: *Typical current harmonics of an arcfurnace, (IEEE 519, [4])*

furnace condition	I_i in % of I_1				
	harmonic order i				
	2	3	4	5	7
initial melting	7.7	5.8	2.5	4.2	3.1
refining	0.0	2.0	0.0	2.1	0.0

$A_{lt} \approx \left(60 \cdot \frac{S_{rA}}{S_k}\right)^3 \approx \left(35 \cdot \frac{S_{kA}}{S_k}\right)^3$ Where S_{rA} the nominal MVA rating of the furnace transformer and S_{kA} the power of short circuit of the furnace and S_{sc} the short circuit of the system.

In 1973 a commission of UIE [1] made an inquiry of 400 arc furnaces in 180 steelworks. As a result a diagram in the fig 3 is made.

For the cases giving a point below the lower curve there were no complains, and for the cases giving a point above the upper curve there were complains of emission of disturbances. For the cases between both curves, there is no definite answer (transition case). In our case we have a point just below lower curve.

In the same reference [1] as an additional criterion for power quality for arc furnaces is a voltage variation of the voltage at PCC. The limit of voltage variation called "momentary" according to Germany is (0.4-0.5)% and according to Norway 0,5% .

3. MEASURING INSTRUMENT

For above-mentioned measurements a commercially available measuring instrument described in [6] is used. It is based on personal computer. With it is possible to measure high harmonics of the voltage and current in all three phases with averaging intervals on choice, 1 sec, 1 min., 10 min. and 15 minutes. A/D conversion is made with 16-bit resolution. The analysis of the measuring data is carried out every second. There are analyzed 8 periods (160 ms) every second and for windowing a Blackman - Harris window is used. The sampling frequency is 5,6 kHz. Flicker measurement is also an option of this instrument, and it can be made in a separate measurement, or the instrument could be programmed to measure in consecutive time intervals high harmonics and flicker. The sampling frequency for flicker measurements is 400 Hz. The momentary flicker values are grouped in groups of 1000 degrees and on the basis of those groups other flicker factors P_{st}, A_{st}, A_{lt} are computed in an off line analysis. The intervals for flicker averaging are 1 or 10 minutes.

4. MEASUREMENT RESULTS

5.1 High harmonics in the feeder of whole steelworks. Those measurements lasted 3 days and were carried out at point 1 (fig. 2). The arc furnace and also steel roll mill were in normal working condition. The averaging period for harmonic

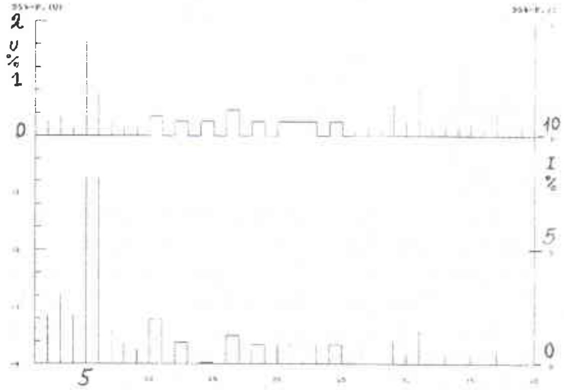

fig 5 *Voltage (above) and current (below) harmonics*

measurements was 1 minute.

For the evaluation of power quality the 95% value for voltage and 99% values for current harmonics are important. On the fig. 4 there are momentary values, and on the fig. 5 the 95 % probability value for voltage and current harmonics are given. In table 6 the 99% probability current harmonics (averaged values of all three phases).

Compared with the standards [3] the reference levels are kept for all voltage harmonics, except the sixth. THD U factor computed with the first 11 harmonic is: $THD\,U = 2\%$

The high content of 6 - Th harmonic is probably due to resonance, because we see both voltage and current 6 - Th harmonic is intensified. There is also resonance at the 29 and 31 harmonics (see fig. 5).

According to recommendation of Argentina for the 5-Th and 6-Th current harmonic the emission limit is excelled, and also according to IEEE 519. The THD I factor for 99% probability is computed (table 6) and found THD $I_{99\%}$ =16% which excels both recommendations. The conclusion is that the steelworks "Zelezara" has excelled the emission limits for current harmonics.

5.2 Flicker measurement. This measurement is made in point 2 of fig. 2, lasted 19 hours and was made with 10 min. averaging time.

Table 6

harmo-nic order n	Ii $_{99}$%	Ui$_{95\%}$
n = 2	3,0	0,25
n = 3	2,9	0,42
n = 4	2,9	0,15
n = 5	10,0	1,62
n = 6	10,8	0,65
n = 7	2,22	0,32
n = 8	1,48	0,15
n = 11	2,38	0,38
n = 13	1,05	0,25
n = 17	1,48	0,38
n = 23	1,17	0,25
n = 29	1,55	0,62
n = 31	1,62	0,68

Fig 7 gives the A_{st} flicker coefficient in one phase, and fig. 6 gives the inverse distribution function of the measuring results. With the graphical construction from fig 8 we get flicker coefficient A_{st} = 9 or 10. Compared with reference level and prescribed emission limits, the flicker values have many times passed them. Also from the fig.6 we see that the emission limits are close to the prescribed limits when the arc furnace doesn't works.

5.3 High harmonics measurement with one second averaging. This measurement was carried out at point 1 of fig. 2 lasted only one hour and was with one second averaging. The measurement period is simultaneous with initial melting period of the arc furnace, when the produced disturbances are biggest. The most prominent current harmonics are shown in the table below (99% probability).

i	2	3	4	5	6	7	8
I_i %	29	62	28	57	117	25	33

Now we could compute THD $I_{99\%}$ = 150% and THD $U_{95\%}$ =1,95%. Fig. 8 gives voltage and current variations every second. Some variation reach 1,5%, which compared with experiences given in [1] are quite big. This data additionally confirms that emitted disturbances from this furnace are high.

5.4 Combined measurement of flicker and harmonics This measurement was made in point 2 of fig 2 as a combined measurement: 20 minutes is flicker measured in 20 intervals of 1 minute averaging, and 4 intervals for harmonics measurements with 10 minutes averaging. The whole measuring time was 4 days. From this measurement we get additional data about current harmonics drawn by the arc furnace.

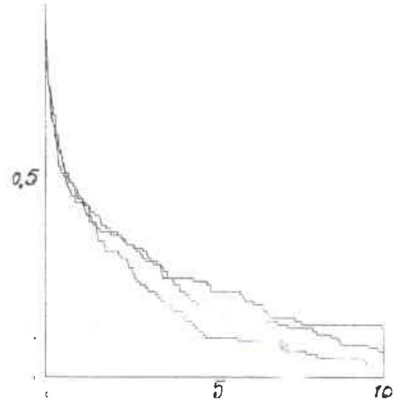

fig. *6 Flicker inverse distribution function*

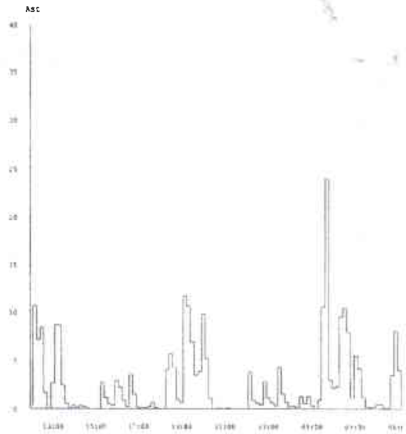
fig. 7 *Flicker over the time*

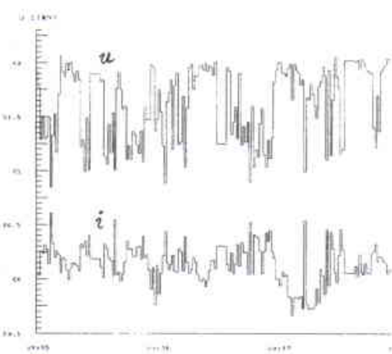

fig. *8 Voltage and current variations in with one sec. averaging*

We compute from the results THD $I_{95\%}$ = 34% and THD $I_{99\%}$ = 36%. The most prominent current harmonics are given in the table below. They are averaged values from all three phases.

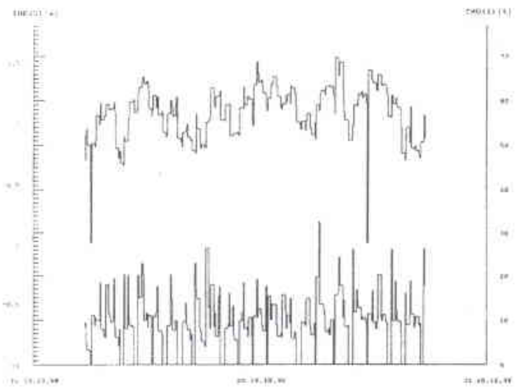

fig. 9 *THD U and THD I for the combined measurement*

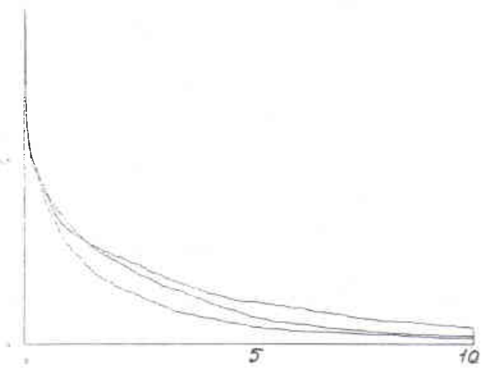

fig. 10 *Inverse distribution function for the flicker*

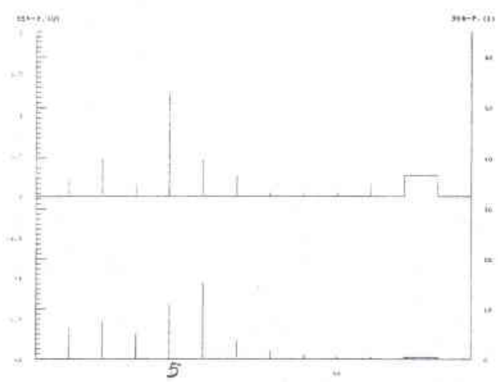

fig. 11 *Voltage and current harmonics (combined meas., 99% probability)*

i	2	3	4	5	6	7	8
I_i %	8,3	9,3	6,8	18,1	27	5,2	2,8

By comparison with the table 2 [3] we see that current harmonics of order 3,4,5,6 and 7 are excelled, and with table 4 [4] that current harmonics of order 2,3,4,5 and 7 are excelled. It can also be seen that both current and voltage harmonics of order 6 are big, that means there is a resonance at that harmonic in the furnace feeder. Fig 9 and 10 are with this measurement From fig. 10 we get 95% probability flicker 5; 5,4 and 9,3 for all three phases.

5. CONCLUSIONS

Evaluation of reference levels and emission limits of power quality in PCC is a complex task. For its successful achievement one needs specialized measuring instrument, recommendations, skilled personnel to work with and to evaluate the results. It also need much time (one week) and costs much.

For this case study we proved that at PCC ("TS Sever") where the arc furnace is connected, is THD U < 2% and that the reference level for all voltage harmonics is met.

Current taken at PCC by the steelworks "Zelezara" shows that some harmonics excel the emission limits, specially the order 3, 5 and 6. THD $I_{99\%}$ = 16% and so it excels the prescribed limit by recommendations. Also there is resonance at harmonic order 6.

The flicker level in 110 kV bussbar in TS Sever is very high and excels 10 to 20 times the reference level. In the time intervals when the furnace is not working, the flicker level is in the prescribed limits. Additional confirmation that the emission of disturbances is high is the voltage variations in one-second averaging harmonic measurement, which was about 1.5%. Obviously this flicker is made by the work of the arc furnace, and not by the steel rolling mill.

The current in arc furnace feeder is also highly distorted and found to be THD $I_{99\%}$ = 36%, as also all low order current harmonic are quite big and excel the prescribed limits. The resonance of 6-Th harmonics seems to be in this feeder. From all these results we conclude that the power of this arc furnace should not be increased without additional technical improvements.

6. REFERENCES

[1]. K.B. Navires: "Ergebnise einer Internationalen Umfrage über die Ruckwirkungen von Lichtbogenstalssmeltzofen auf elektrische Versorgungsnetze", *Elektrowärme International*, Ed.3.No 6., 1974.

[2]. VDEW: *"Grundsätze für Beurtelung von Netzrückwirkungen"*, 3 überarb. Ausgabe, 1992

[3]. T. Gomes San Roman, J. Roman Ubeda: "Power Quality Regulation in Argentina: Flicker and Harmonics", *IEEE Trans. on Power Delivery*, Vol. 13, No. 3, July 1998

[4] IEEE Std 519-1992: *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"*.

[5] IEC Standards of series 1000, *"Electromagnetic Compatibility"*.

[6] L. Nikoloski, G. Rafajlovski, V. Malinovski: "Investigation of Electric Power Quality in the Distribution Power System of Republic of Macedonia", *MELECON 98*, pp. 1018-1022.