Improvement of Technological and Electric Performances for Plate-Type Electrostatic Precipitators with Three Sections

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Abstract: - The plate-type electrostatic precipitators have long been used by industry applications as the preferred method for controlling pollution with dust particles. The paper analyze the collection efficiency, for electrostatic precipitators with three sections (still, there is in industry applications), when are used different voltage supplies of electrostatic precipitators sections, the gas particles mass distributions, element average V-I curves, onset Corona voltage, spark discharge voltage, current density, collection efficiency, the inlet and the outlet dust concentration for different energization of sections. It's been performed an analysis of the total harmonic distortion coefficient of the current absorbed by the source, the supply voltage, the apparent and active power (for fundamental and harmonics), and the power factor (global, fundamental's and deforming) in situation when the current's value from the ESP field was superiorly limited.

Key-Words: - Pollution, Electrostatic precipitators, Collection efficiency, Total harmonic distorsion

1 Introduction

The globalization of the environmental pollution problems caused by the increase of industrial production will lead in the cleaning of the waste gases. The basic idea of electrostatic precipitators is to give the particles an electrostatic charge when are place them into an electrostatic field that drives the particles to a collecting plates (electrodes) connected to earth. The dry plate-type electrostatic precipitators (ESP) are used in industry applications to controlling pollution with dust particles.

This type of ESP is used to remove pollutants from large flow gas (hundreds of thousands m^3/h). The efficiency of ESP's depends on voltages waveform and amplitude, type of power supply, current control, geometry of electrostatic precipitators, type of discharge wires, gas composition, particles distribution, gas flow, temperature, gas pressure and particles velocities distribution [1,2,3,4,5,6].

The structure of ESP, generally, is made from a number 3÷4 of series sections; each of them is energized by it power supply. One of software that computes the plate-type electrostatic precipitators performances is ESPVI 4.0.a [4,7].

In the modeling with ESPVI 4.0.a software are used parameters from thermal power plant plate-type electrostatic precipitators (from Romania) [8,9,10]. The ESPVI 4.0.a software has a lot of ESP's parameters [7]:

- the technological ESP parameters;
- the electrical ESP parameters for every sections;
- the gas parameters;
- the dust parameters.

With this software and with the technological and electrical parameters from industry may be compare the performance of plate-type electrostatic precipitators for understanding how does it work.

The collection efficiency of ESP increase, generally, with the sections number. Adding a new section, for ESP with three sections, it is a solution that must be analyse practical and economical (a new section may be a too expensive solution).

2 The Plate-Type Electrostatic Precipitators Performances Used in Simulations and Measurements

In the modelling with ESPVI 4.0.a software it is used ESP's with three sections (no. 4, 5, 6) from Thermal Power Plant Mintia-Deva, Romania (1200 MW, 6 electrical groups, each of them 200MW) [8,9,10]. Because treat large gas flow, the ESP's are divide in three sections. Every sections has two fields for reliability, every section has own electrical supply. The discharge wires are disposed in the ducts and are equidistant.

Table 1

The main electrical characteristics for ESP’s supplies from Thermal Power Plant Mintia-Deva, Romania

The main electrical characteristics	ESP no.4	ESP no.5	ESP no.6
The supply number [-]	6	6	6
The low voltage supply	2x380 V ±10% 50 Hz	2x380 V ±10% 50 Hz	2x380 V ±10% 50 Hz
The nominal supply current [A]	607	595	595
The ESP peak high voltage [kV]	111	111	111
The ESP nominal high voltage [kV]	65	65	65
The ESP maximal current [mA]	2800	2800	2800
The ESP nominal current [mA]	2000	2000	2000
The apparent power [kVA]	237.2	238	238

Table 2

The main technological characteristics for ESP’s supplies from Thermal Power Plant Mintia-Deva, Romania

The main tehnological characteristics	ESP no.4	ESP no.5	ESP no.6
The number sections	3	3	3
The height of collecting plates (electrodes)	12	12	12
The distance between the collecting plates and the discharge wires [m]	0.3	0.3	0.3
The duct number from sections	54	55	56
The nominal gas stream flow [m^3/h]	728900	728900	675000
The inlet dust concentration (from design) [mg/m^3]	85.69	93.61	93.61
The outlet dust concentration (from design) [mg/m^3]	0.75	0.889	0.889
The collecting efficiency [%]	99.12	99.05	99.05
The nominal temperature of inlet gases [^{0}C]	148	148	148
The maximal temperature of inlet gases [^{0}C]	163	163	163
The nominal ashes flow, evacuate from ESP [t/h]	44.5	44.5	44.5
The unburn combustible from ashes [%]	0.3-1.2	0.3-1.2	0.3-1.2
The gas viscosity [kg/(m/s)]	$(1\text{-}5)\cdot 10^{-5}$	$(1\text{-}5)\cdot 10^{-5}$	$(1\text{-}5)\cdot 10^{-5}$
The inferior calorific power of coal [kcal/kg]	2750	2450	2450
The dust resistivity [Ω·cm]	10^9-10^{13}	10^9-10^{13}	10^9-10^{13}

Upgrading mostly means taking account a stricter inlet and outlet requirements results the emission limits [11]. The effect of flue gas conditioning systems can reduce the number of ESP sections.

A substantial improvement of overall efficiency can be achieved by optimizing flow distribution in the ESP. International inquiries for ESP’s most time require internal gas distribution to be in strict accordance with standards. Many improvements of ESP’s can make using the advantages of increasing the spacing between discharge wires and collecting plates. Modification of high voltage supply systems it is other solution to improve performances.

This applies in general to changes of pass spacing and sometimes also to change electrode geometry. On the other hand, there are a number of applications which would no modernization of the power supply equipments, depending on the behavior of V-I characteristics. If is back Corona (back ionization) the modernization of electrical equipments will be necessary.

Adding active ESP section will normally be a less effective and a more expensive way to increase ESP performances than increased electrode height, is an economical solution [1,2,4].

3 Simulations and Measurements of Technological and Electrical Parameters Using ESPVI 4.0.a Software

The ESPVI 4.0.a (Electrostatic Precipitators U-I Curves and Performance Model) software is from 1992. The ESP's model from ESPVI 4.0.a software can simulate electrical and technological parameters, under several conditions, including high resistivity ashes, the use of rectified current and intermittent energization of ESP sections, different size of dust particles (up to 1000μm) [4,7,12].

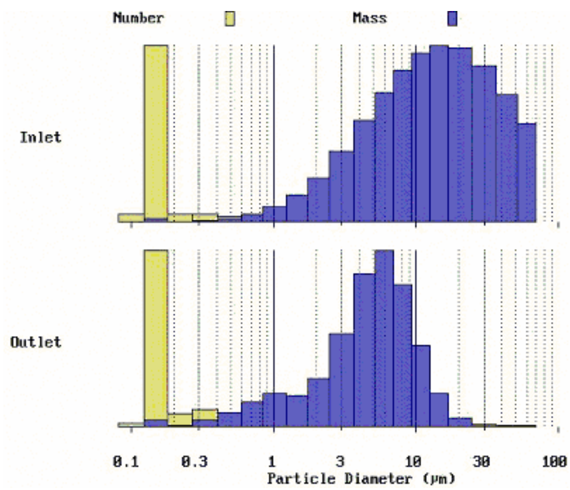

Fig.1. Distribution of dust particles depending on number and mass, at input and output

The simulations presented further were achieved taking into account the real electric and technological parameters of the ESP's no. 4,5,6 from the Thermal Power Plant Mintia-Deva.
From fig.1, one can notice that at input into ESP, the particles with diameters between 5-40 μm have the greatest mass, and at output from ESP the particles with diameters between 3-10 μm have the greatest mass. The representation from fig.1 was achieved in relative measures.

An economical solutions (saving energy) is using of intermittent energization of ESP section. The power supply has the same structure with power supply with d.c. energization (with high voltage bridge), but the control of power devices (thyristors) from power supply is different.
The principle of intermittent energization is one ESP current pulse and than a number of current pulses are suppressed (i.e. two current pulses suppressed for three degree intermittent energization).

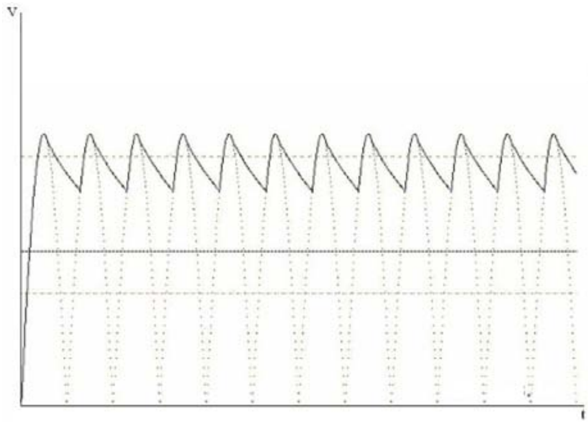

Fig.2. Voltage shape in ESP section depending on time, for d.c energization with high voltage diode bridge

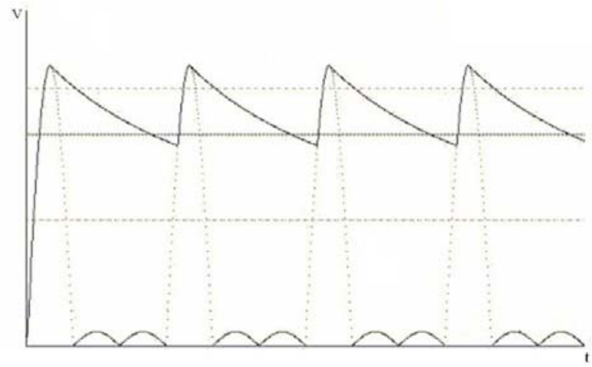

Fig.3. Voltage shape in ESP section depending on time, for intermittent energization (3 degree)

The voltages shapes from fig.2 and 3 are used in simulation of the current density depending on voltage in every section of ESP, for d.c energization and for intermittent energization.
In fig.4,5,6,7,8,9 are graphics of the current density for each discharge wire from a section depending on voltage between electrodes.

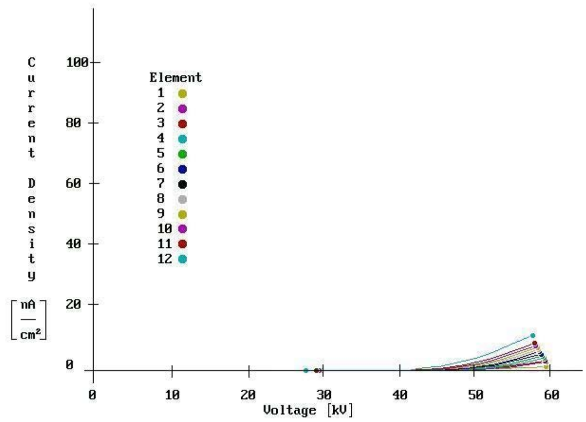

Fig.4. Element average V-I curves under load, section 1, d.c energization with high voltage diode bridge

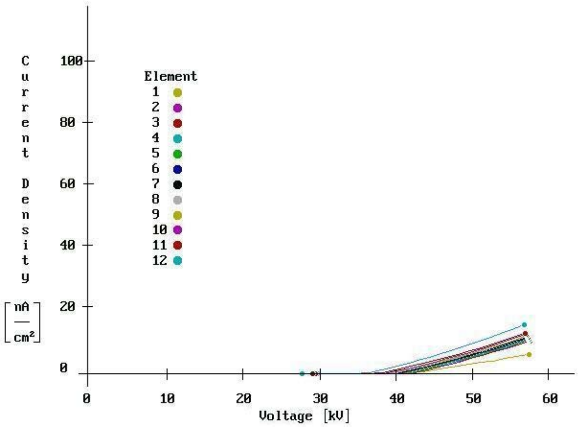

Fig.5. Element average V-I curves under load, section 2, d.c energization with high voltage diode bridge

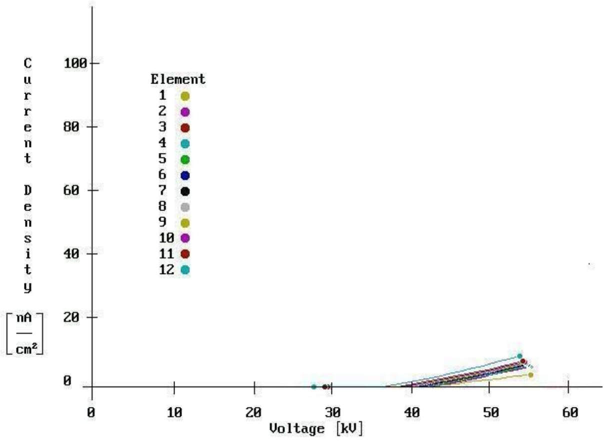

Fig.8. Element average V-I curves under load, section 2, 3 degree intermittent energization

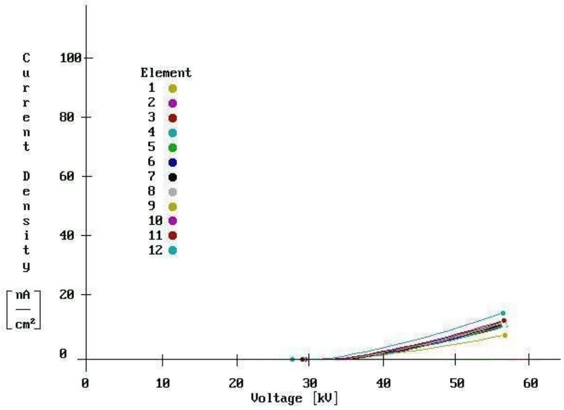

Fig.6. Element average V-I curves under load, section 3, d.c energization with high voltage diode bridge

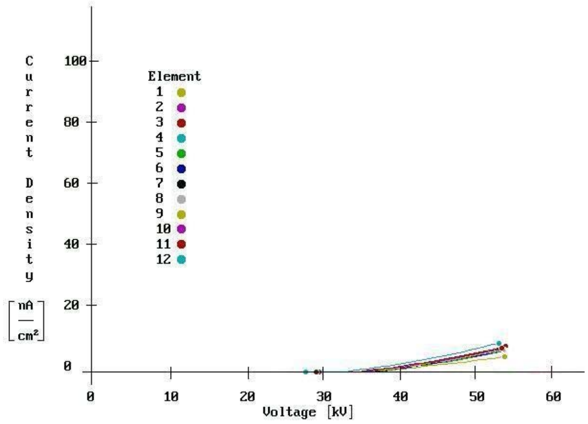

Fig.9. Element average V-I curves under load, section 3, 3 degree intermittent energization

When the sections are supplied in DC with high-voltage rectifier bridge (fig.4,5,6), the onset Corona voltages and spark discharge voltages are different from an electrode to another [13]. Towards the last element from each section, the current density is higher and higher.

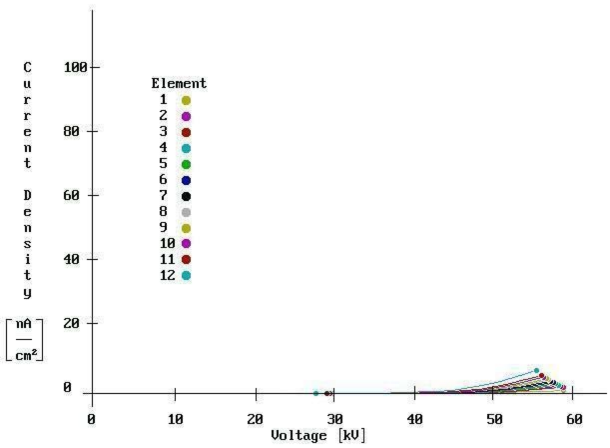

Fig.7. Element average V-I curves under load, section 1, 3 degree intermittent energization

In case of supplying the sections in intermittent energization (fig.7,8,9), the current density for the same element, from the same section, has smaller values than the previous case (fig.4,5,6). With this type (intermittent) of power supply, the ESP's collecting performances are not affected. This method is used for the medium and high resistivity dusts.

In fig.10,11,12 were simulated the main current-voltage characteristics (the onset Corona voltage, the spark discharge voltage and the spark current) in the case of ideal d.c. energization (DC), d.c. energization with high voltage bridge (1:01), d.c. energization with one diode (1:02), and intermittent energization (1:03, 1:05, 1:07, 1:09).

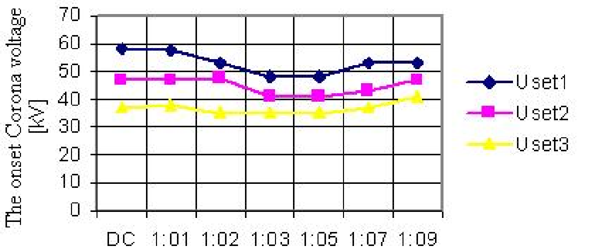

Fig.10. Onset Corona voltage for every section (1, 2, 3) when the ESP sections are supplied with the same voltage

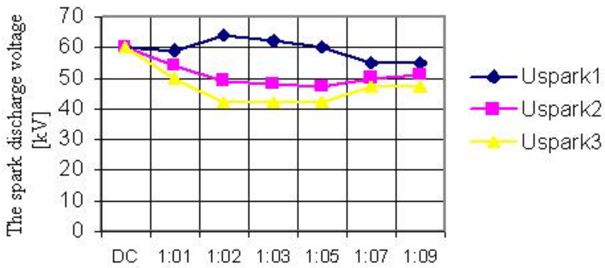

Fig.11. Spark discharge voltage for every section (1, 2, 3) when the ESP sections are supplied with the same voltage

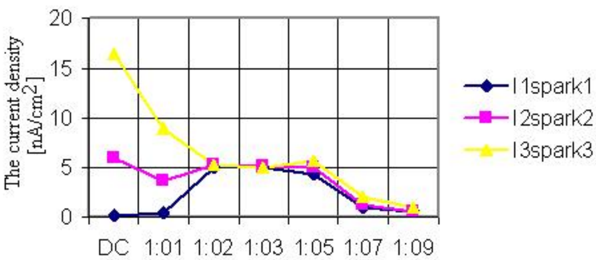

Fig.12. Current density in the case of spark discharge for every section (1, 2, 3) when the ESP sections are supplied with the same voltage

The collecting efficiency depending on the voltage supply is present in fig.13, when the supply section, for every section, is the same type.

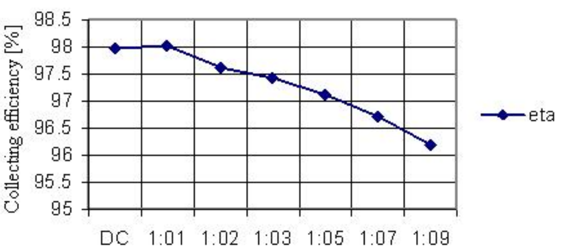

Fig.13. Collecting efficiency depending on the voltage supply

The onset Corona voltage it is the same for every sections, indifferently by the voltage waveforms. The onset Corona voltage for section 1 is bigger than the onset Corona for section 3 (fig.10).

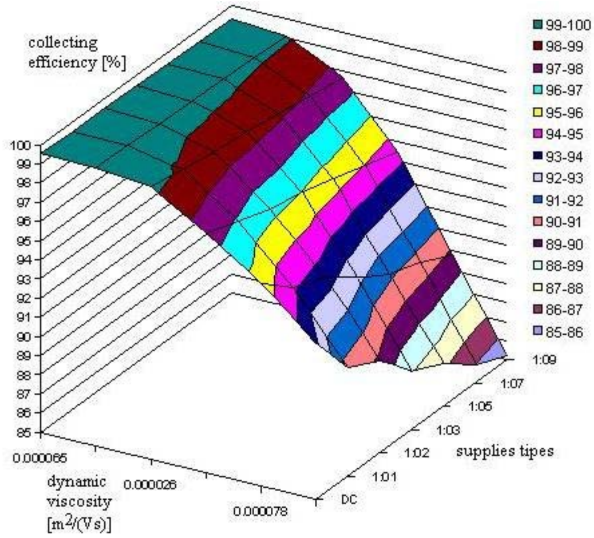

Fig.14. Collecting efficiency depending on the voltage waveforms and gas dynamic viscosity

This observation is available for spark discharge voltage (fig.11). The current density, for intermittent energization 1:03,…, 1:09 is smaller for section 1 and bigger for section 3 (fig.12).

The best collecting efficiency is when are supplies every sections with DC voltage (ideal) and full wave voltage (98%) and the worst collecting efficiency when is used intermittent energization 1:09 (96.15%). The fields of ESP do not supply with the same source type to obtain maximum performances [5,14].

Fig.14 presents the collecting efficiency depending on dynamic viscosity and the voltage waveforms. The collecting efficiency is diminishing, when the dynamic viscosity and intermittent degree energization are lower.

It is note with q_i[g/m^3] the inlet dust concentration and with q_f[g/m^3] the outlet dust concentration for an ESP's. The ESP collection efficiency η[-] is:

$$\eta_1 = 1 - \frac{q_f}{q_i} \,. \qquad (1)$$

Let consider an ESP's with n sections (fig.15). Practically, the maximum number of sections is up to 10. At the outlet of n-1 sections, the dust concentration is q_{n-1} [g/m^3].

The collection efficiency η_1[-] of section 1 is:

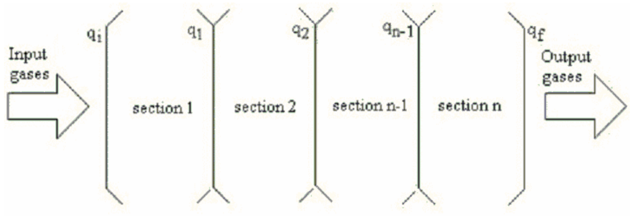

Fig.15. Electrostatic precipitators with n sections

$$\eta_1 = 1 - \frac{q_1}{q_i}. \quad (2)$$

The collection efficiency η_2[-] of section 2 is:

$$\eta_2 = 1 - \frac{q_2}{q_1}. \quad (3)$$

Table 3
The measured and simulated collection efficiency for different ESP's with three sections

	Case number	q_i[g/m^3]	q_f[g/m^3]	Measured collection efficiency η_m [%]
ESP 4	1	24.908	0.147	99.408
	2	25.528	0.138	99.459
	3	24.127	0.154	99.362
ESP 5	1	20.746	0.187	99.098
	2	20.061	0.198	99.013
ESP 6	1	20.593	0.167	99.189
	2	26.464	0.113	99.573

	Measured average collection efficiency η_{avg} [%]	Simulated collection efficiency η_s [%]	Relative error $\frac{\lvert\eta_m - \eta_s\rvert}{\eta_m}100$ [%]
ESP 4	99.41	98	1.41
ESP 5	99.055	98	1.06
ESP 6	99.381	98	1.39

The collection efficiency η_n[-] of section n is:

$$\eta_n = 1 - \frac{q_f}{q_{n-1}}. \quad (4)$$

From relations (1), (2), (3), (4) result the total collection efficiency:

$$\eta = 1 - (1-\eta_1)\cdot(1-\eta_2)\cdot\ldots\cdot(1-\eta_n). \quad (5)$$

The total collection efficiency depends on every sections collection efficiency.

Table 4
The measured average diameter of dust collecting in ESP sections

	d_{avg1} [μm] section 1	d_{avg2} [μm] section 2	d_{avg3} [μm] section 3
ESP 4	79.7	45.15	50.68
ESP 5	73.4	45.5	56.3
ESP 6	74.6	38.7	38.6

From table 3 [8,9,10] results that the simulated collection efficiency is close by measured collection efficiency (the relative error is between 1.06-1.41 %). That demonstrated the performance of prediction model from ESPVI 4.0.a software. From table 4 [8,9,10] results that the average diameter of inlet dust particles is smaller comparatively with the average diameter of outlet sections.

4 Power Supply Diagram

In fig.16 is presented the principle diagram for the power supply of a field. This power supply diagram (fig.16) is used at the ESP's of the energetic groups no.4, 5 and 6 from the Thermal Power Plant Mintia-Deva.

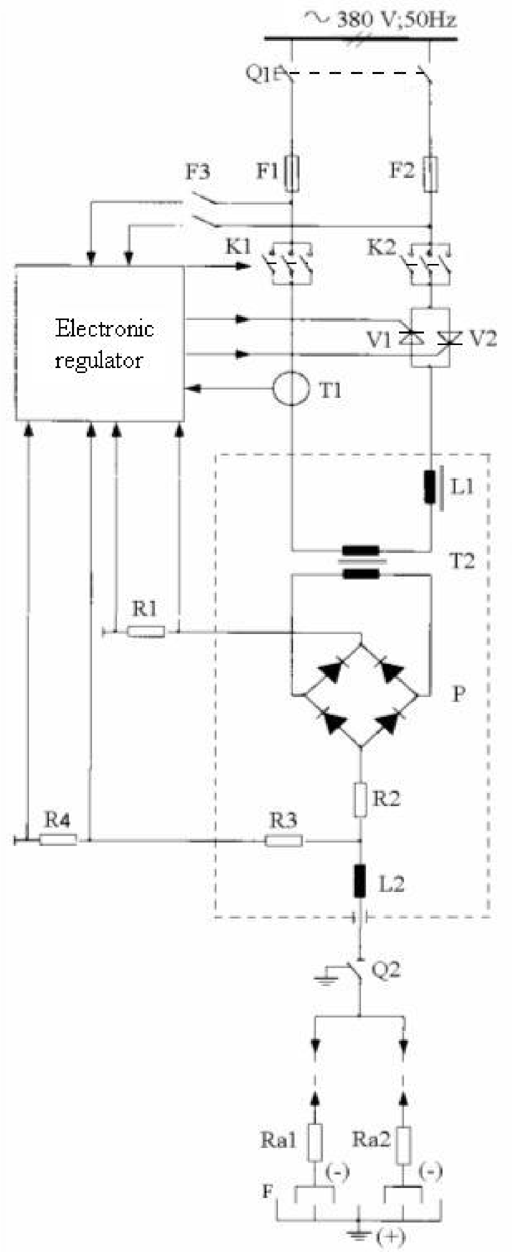

Fig.16. Power supply of a field

Because the absorbed power is of tens of kW (sometimes even hundreds of kW), a power supply unit for a field is usually supplied from two phases of the three-phased system (380 V a.c.). The unit is using a separator Q_1 and a protection system with fusible fuses F_1 and F_2 (for the power part). The absorbed currents are of hundreds of amperes, therefore, sometimes are used two contactors on each phase K_1 and K_2. On one phase are mounted two thyristors V_1 and V_2 in anti-parallel, to adjust the average value of the voltage applied to the bootstrap transformer's primary T_2 (i.e. 380 V/65 kV, 50 Hz, S=238 kVA). After the voltage was raised (at values of tens of kV), the alternating voltage is rectified with a rectifying bridge P, the negative potential is applied to the discharge wires, and the positive one to the collecting plates which are also grounded [15].

The automatic control is ensured by an electronic regulator which gets information from the transformer T_1 about the current from the primary circuit, from the resistance R_1 (shunt; i.e. R_1 =1.25 Ω, P=3 W, to a current of 800 mA from the circuit it corresponds 1 V c.c.) about the current from the secondary circuit, and from the resistive divisor R_3-R_4 (to a voltage of 150 kV corresponds 10 V c.c.) about the secondary voltage [16].

The signals are transmitted towards the control devices as current between 4 – 20 mA. By means of the electronic regulator is controlled the opening angle of the thyristors V_1 and V_2 or, lately, is achieved the intermittent control (a certain current pulse is left to pass, usually odd 3, 5, 7). In order to limit the short-circuit currents, is used a limiting primary reactor L_1 (i.e. L_1 =0.7 mH).

To avoid the penetration of the harmonics due to the discharges that take place in the ESP from the mains, is used a high-frequency blocking reactance (without magnetic core) L_2 (i.e. L_2 =60 mH with R_2=7 Ω) and a dampening resistance R_a (R_a=80 Ω). Q_2 is a high-voltage grounding separator.

5 Measuring and Analysis of Currents and Voltages in ESP fields

It's been taken measurements of the current and voltage from the primary power supply circuit for an ESP field. To perform the analysis of some non-sinusoidal signals' measurements, few notions are used [17]. Further, to be able to make the calculations, for the current's and voltage's harmonics the maximum rank is considered to be equal with 40. The total harmonic distortion coefficient of the current is defined by:

$$I_{THD} = \sqrt{\sum_{i=2}^{40}\left(\frac{I_i}{I_1}\right)^2}\cdot 100 \qquad [\%] \qquad (6)$$

where I_i is the effective value of the rank i harmonic current, and I_1 is the fundamental's effective value. Similarly, can be determined a total harmonic distortion coefficient for voltage:

$$V_{THD} = \sqrt{\sum_{i=2}^{40}\left(\frac{U_i}{U_1}\right)^2}\cdot 100 \qquad [\%] \qquad (7)$$

where U_i is the effective value of the rank i harmonic voltage, and U_1 is the fundamental's effective value. The apparent power of the order 1 harmonic is:

$$S_1 = U_1 \cdot I_1 \qquad [VA] \qquad (8)$$

The current's effective value is determined with:

$$I = \sqrt{\sum_{i=1}^{40} I_i^2} \qquad [A] \qquad (9)$$

The active power of the order 1 harmonic is:

$$P_1 = U_1 \cdot I_1 \cdot \cos\varphi_1 \qquad [W] \qquad (10)$$

The active power's deforming residue:

$$P_d = \sum_{i=2}^{40}\left(U_i \cdot I_i \cdot \cos\varphi_i\right) \qquad [W] \qquad (11)$$

φ_i[^{0}] is the phase displacement between U_i and I_i.

$$k_{dp} = \frac{P_1}{S_1} + \frac{P_d}{S_1} = k_{pf} + k_{pd} \qquad [-] \qquad (12)$$

k_{dp} – global power factor, k_{pf} – fundamental's power factor, k_{pd} – deforming power factor.

Further, are presented measurements of the current and voltage on the primary part for the field no.3, ESP no.5 from the Thermal Power Plant Mintia – Deva.

At the energetic group no. 5 there are two ESPs named 5A and 5B which can filter together up to 2x728900 m^3/h. Each ESP has three fields, each field being supplied from an each separate source (fig.16) with the electric characteristics of the source presented in table 1. The adjustment of the Corona power was made depending on the secondary current's limitation (for different values of the secondary current from the ESP field).

To ensure a high flexibility, each field is divided in two sections. An ESP has thousands of discharge wires that can break-up from different causes and which could put out of operation the respective zone. Thus, if a defect appears in the respective zone from ESP, the respective section or field is isolated (is not supplied with voltage anymore). For supplying the ESPs 5A and 5B are used 6 groups. The distance between the discharge wires and the collecting plates is of 350 mm.

The following measurements (fig.17-21) were made in case when the secondary current I_s (from the ESP field) was limited to the maximum value of 902 mA d.c. (case I). Starting from the current's and voltage's wave shapes (in one period), was determined the apparent power (in one period), then, using the Fast Fourier Transform, were calculated the amplitudes for the first 40 harmonics, both for current and for voltage (specters of harmonics).

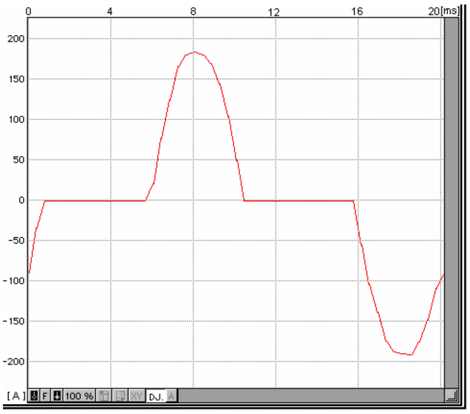

Fig.17. Primary current (case I)

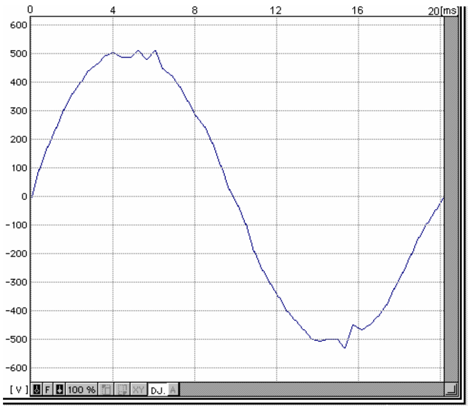

Fig.18. Primary voltage (case I)

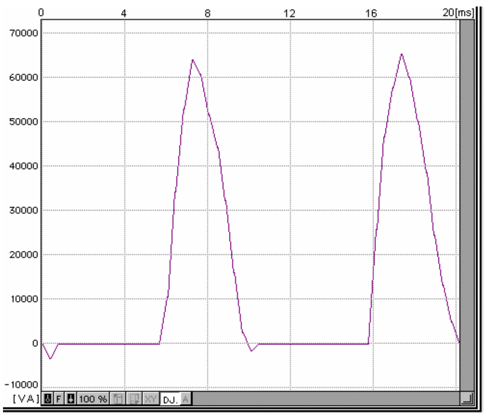

Fig.19. Apparent power (case I)

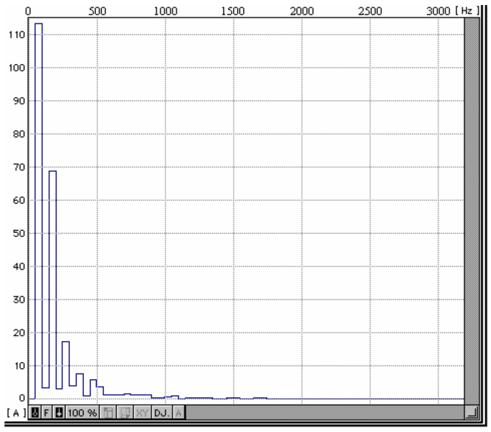

Fig.20. Current harmonics' amplitudes (case I)

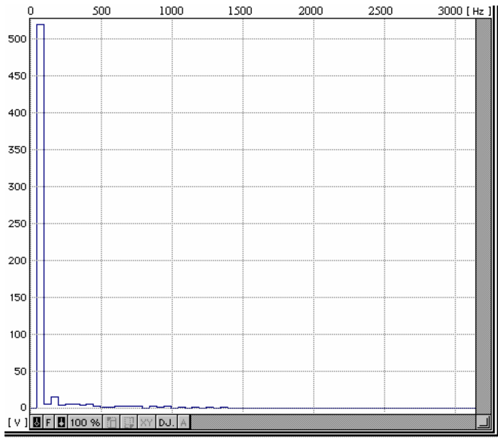

Fig.21. Primary voltage harmonics' amplitudes (case I)

The second case (case II) is using a limitation of the secondary current I_s at the maximum value of 701 mA d.c., and the third case (case III) is using a limitation of the secondary current I_s at the maximum value of 589 mA d.c.

Using the relations (6)-(12) were calculated these measures for the three cases (table 5).

The global power factor k_{dp}, the fundamental's power factor k_{pf} and the deforming power factor k_{pd} decrease by current's decrease.

By decreasing the current absorbed from the mains, I_{THD} increases, exceeding the limits from norms. Is imposed the utilization of some filters to diminish the harmonics 3, 5 and 9. V_{THD} is under the limit established by standards (<8%).

Is made an analysis of the measured current and voltage harmonics' amplitudes and the permitted limit levels for the deforming regime's parameters according to IEC 61000-2-2 and IEC 61000-3-4 [18,19].

Table 5
Determination of the electric measures by the relations (6)÷(12)

	I_{THD} [%]	V_{THD} [%]	S_1[kVA]
Case I	62.8	3.7	30.227
Case II	68.6	3.63	20.272
Case III	77.5	3.6	17.81
	I [A]	P_1 [kW]	P_d [kW]
Case I	94.65	16.017	0.514
Case II	63.38	8.886	0.339
Case III	61.48	7.526	0.159
	k_{pf} [-]	k_{pd} [-]	k_{dp} [-]
Case I	0.529	0.017	0.546
Case II	0.438	0.0167	0.455
Case III	0.422	0.0089	0.431

Further (fig.22÷25) is made a comparative analysis between the measured amplitudes (black) and the permitted ones (white) according to norms.

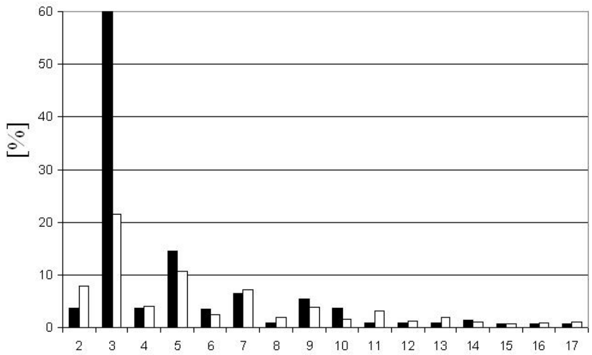

Fig.22. Current harmonics' analysis (case I)

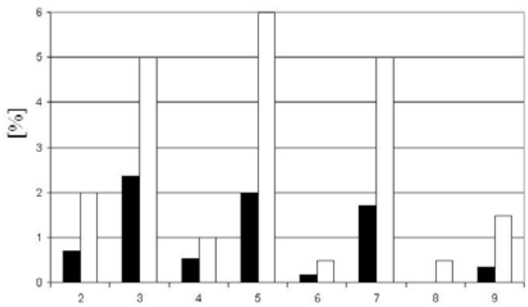

Fig.23. Voltage harmonics' analysis (case I)

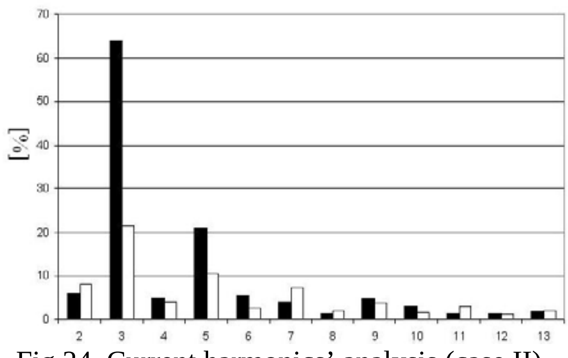

Fig.24. Current harmonics' analysis (case II)

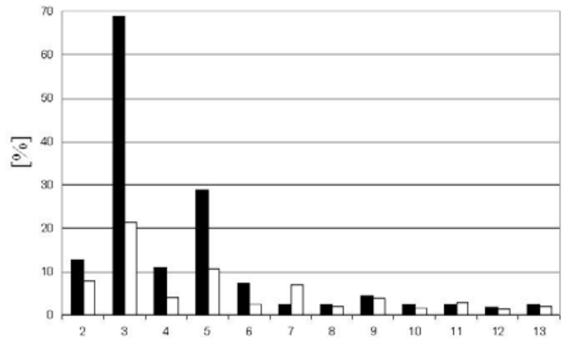

Fig.25. Current harmonics' analysis (case III)

In fig.22,23,24,25 on the horizontal axe is the harmonic rank.

Some current harmonics (of rank 3, 5 and 9) exceed the limits established by norms. Even the supply voltage wave shape is different from the sinusoidal shape the voltage harmonics don't exceed the values from norms.

6 Conclusions

The collection efficiency of ESP depends on voltage waveforms, among other factors. Is necessary to supply with different shapes voltage from section to section (depending on dust resistivity) to obtain high collection efficiency. The dust resistivity rise up to outlet section. The inlet section may be supply with DC voltage (ideal) or full wave voltage with high voltage bridge, for well charge of dust particles with normal resistivity. The outlet section may be supply with intermittent voltage (with different degree of intermittence) to collect dust particle with high resistivity.

The upgrading of ESP's it is a difficult problem that must be analyse practical and economical.
An improve solution of collection efficiency for ESP with three sections is to add a new section. That is an expensive solution and must be analyse other solutions to improve collection efficiency of ESP.

The power supply sources of a field for an ESP are alternating voltage variators which determine an I_{THD} higher than the one established by norms (the higher I_{THD}, the smaller the absorbed current).

To diminish the current harmonics, should be used filters for the harmonics 3, 5 and 9. The power factor decreases by decreasing the current absorbed from the mains. The power factor's improvement should be achieved after diminishing the current harmonics.

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