Considerations on the Current Harmonics of Plate-Type Electrostatic Precipitators Power Supplies

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***Abstract*—Plate-type electrostatic precipitators are the main installations of separating particles from industries (especially for large gas flow) and must operate in its electromagnetic environment without interfering with the operation of other equipments. The power supplies have non-linear elements that cause distortions of the sources currents. The main objective of this work is to analyze measure and simulate currents, voltages and powers from the sources that are used (thyristor-controlled reactor type) taking into account a new electric model, more close to reality, of the ESP sections. It's analyzed the modification of the current waves shape and THD in case of using passive filters.**

***Index Terms*—Electrostatic precipitators, Power harmonic filters, Power supplies, Total harmonic distortion.**

I. INTRODUCTION

In the last decades the use of power electronics equipments has quickly increased. The power electronics technology and its progress depend on the advantages of semiconductor technology [1], [2].

The plate-type electrostatic precipitators (ESPs) have been used to collection the dust, fume, and mist particles from following processes: electrical power plants, cement industry, iron steel works, glass industry, and other industries.

The ESPs are made from a number (usually, three or four in the most applications) of series sections. Each section is energized by its own thyristor-controlled reactor (TCR), high voltage transformer, rectifier set bridge, and has its own hopper. By mechanical shock, the dust particles are removed from the collecting plates into receiving hopers [3]–[5].

The most popular power sources used for supplying ESP sections are those which are supplied from two phases, with two thyristors connected as anti-parallel which, by controlling the ignition angle, modify the effective voltage in the transformer's bootstrap primary and directly the voltage on the ESP's section.

The two thyristors are in heavy-duty regime and they must be properly dimensioned [6], [7].

An important problem in simulations' achievement is the modeling, as accurate possible, of the ESP's sections.

The current absorbed by the electronic power sources is non-sinusoidal and is more deformed as the ignition angle is higher [6]–[10].

A solution to reducing currents harmonic is to use passive filters, that have LC filters and high pass filter. Passive filter have some disadvantages: it is possible to fall into series or parallel resonance with the source and produces harmonic currents, and, also, the passive filter performances depends on source impedance (usually unknown) [8]–[10].

The power sources that supply the ESP sections, depending on the constructive solution, the operational diagram and the voltage's adjusting regime determine and increased safety and efficiency for collecting the dust from the gas result further different industrial processes [11]–[13].

Today, there is powerful software (PSCAD/EMTDC, MATLAB) and PCs that provide many useful low cost solutions in the design and analyze the power electronic sources. Usually, the electric power systems are complex.

PSCAD/EMTDC is a simulator of electric networks with the capability of modeling complex power electronics and controls of the non-linear networks. When run under the PSCAD graphical user interface, the PSCAD/EMTDC 4.2 combinations becomes a powerful means of visualizing the enormous complexity of portions of the electric power systems [14].

II. ANALYSIS OF A TRADITIONAL DC ENERGIZATION FOR ESP SECTIONS

The A plate-type ESP consists of emission electrodes (of different shapes) connected to a high negative voltage of tens of kV, installed between the collecting plates (collecting electrodes) which are connect to the ground. Supplying the electrodes with high voltage generates an electric field. The electric field is stronger in vicinity of the discharge electrodes (10–60 kV/cm) and has low values near the collecting plates (2–4 kV/cm). It is the area near the discharge electrodes where the electrostatic charging process

Manuscript received August 30, 2012; accepted February 05, 2013.

This paper was supported by the project "Development and support for multidisciplinary postdoctoral programs in primordial technical areas of the national strategy for research - development - innovation" 4D-POSTDOC, contract no. POSDRU/89/1.5/S/52603, project co-funded from the European Social Fund through the Section Operational Program Human Resources 2007-2013.

develops. The shape of the discharge electrodes has an important role in electric charge carriers generating.

A. Mathematical model of the current

One of the main structure power electronic is TCR that is a group of anti-parallel thyristor controlled an inductor and the reactance is varied continuous by partial conduction control of the thyristor (Fig. 1).

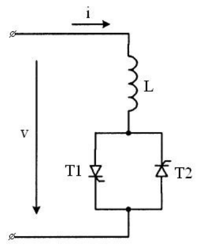


Fig. 1. Thyristor-controlled reactor (TCR) principle.

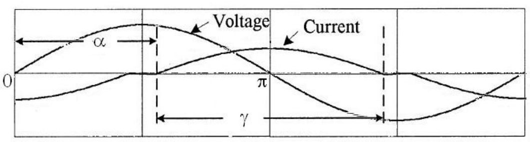


Fig. 2. Voltage and current through TCR.

The TCR is supplied at A.C. voltage and the control principle is called phase control. In general, instead of reactance L is an impedance Z [6]. In Fig. 2, α is firing angle and γ is conduction angle. The instantaneous current is [6], [7]:

$$\begin{cases} i = \dfrac{\sqrt{2}\cdot V}{Z}\left(\cos\alpha - \cos\omega\cdot t\right), \alpha < \omega\cdot t < \alpha+\gamma, \\ i = 0, \alpha+\gamma < \omega\cdot t < \alpha+\pi. \end{cases} \quad (1)$$

If α increase on the one hand the power on the impedance decrease and on the other hand the current waveforms through impedance becomes less sinusoidal. For the same α angle for both thyristors the even order harmonics and the D.C. current components are zero and are generated only the odd order harmonics.

The RMS current value for n^{th} current harmonic is given by [7]

$$I_n = \frac{4\cdot V}{\pi\cdot Z}\left[\frac{\sin(n+1)\cdot\alpha}{2\cdot(n+1)} + \frac{\sin(n-1)\cdot\alpha}{2\cdot(n-1)} - \cos\alpha\cdot\sin\frac{n\cdot\alpha}{n}\right]. \quad (2)$$

In (2), n=3, 5, 7, ... The current conduction angle is maximum 180^0 in anti parallel thyristors configurations. The effective value for a periodic current is

$$I = \sqrt{\frac{1}{T}\int_0^T i^2 dt}\ . \quad (3)$$

The effective value also may be compute with a D.C. (I_{DC}) and harmonic currents

$$I = \sqrt{I_{DC}^2 + I_1^2 + I_2^2 + \ldots + I_n^2}\ , \quad (4)$$

where I_1 is the effective current at 50 Hz, and I_n is the effective current at n x 50 Hz. In practice, n is limited to 40.

The total harmonic distortion (THD) for source current is:

$$THD = \sqrt{\frac{\sum_{k=1}^{n} I_k^2}{I_1^2}}\cdot 100[\%]\ . \quad (5)$$

B. Traditional DC energization of a section

The traditional D.C. energization is obtained with the electrical power supply presented in Fig. 3 [4].

The line voltage is regulated by a thyristor controller T_1-T_2 through phase control by a pair of anti parallel thyristors. After that, the voltage is applied to the primary of the high voltage transformer VT_2.

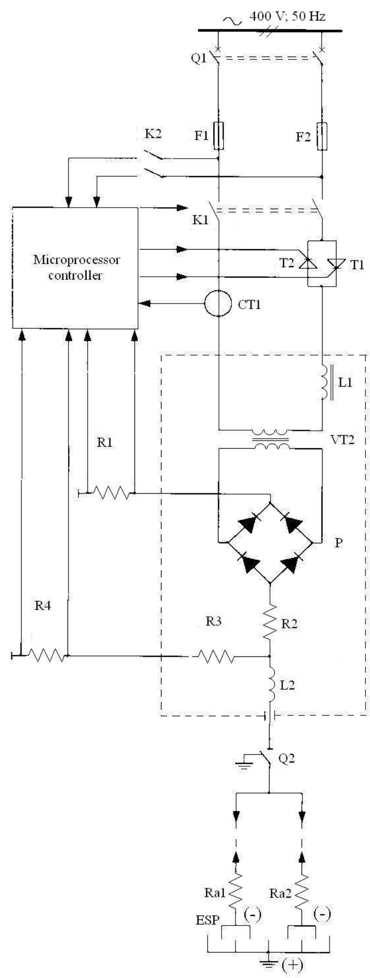


Fig. 3. Electrical power supply for a section.

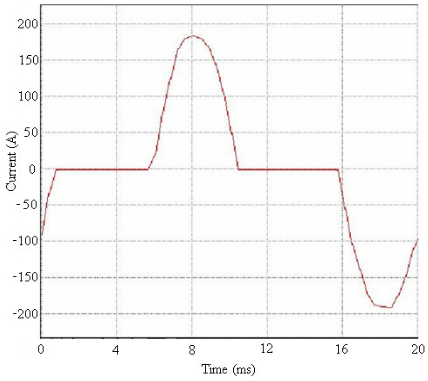
The primary voltage is raised to the desired secondary level and the A.C. voltage is rectified by a high voltage bridge rectifier P. The rectified secondary voltage is applied to a section of electrostatic precipitators through current filter R_2-L_2. The high voltage rectifier is connected in such a way that the discharge electrodes have a negative polarity (negative Corona is generated in the precipitator to the discharge wires) and the collecting plates are earthed.

III. MEASUREMENTS RESULTS

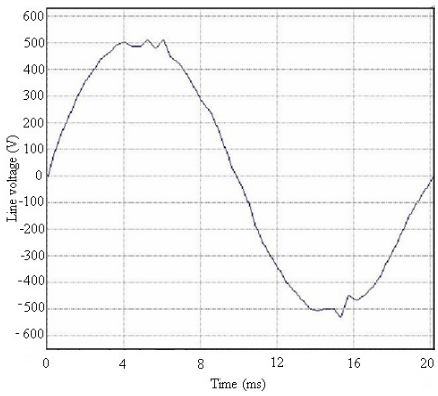
The parameters were measured (with different devices) at a section of a large electrostatic precipitator (appendix) from a thermal power station [4].

Any periodical waveform can be composing into a sinusoidal waveform at the fundamental frequency (50 or 60 Hz, depending on the network area) plus a number of sinusoids at harmonics frequencies. For symmetrical waveforms (positive and negative half cycles are the same shape and magnitude), the even numbered harmonics are zero. In practice, may be occurs smalls even harmonics and D.C. component.

The measured primary source current and voltage, for a section of ESP are present in Fig. 4 (current through section was 0.902 A), the spectrum for primary source current and voltage in Fig. 5.



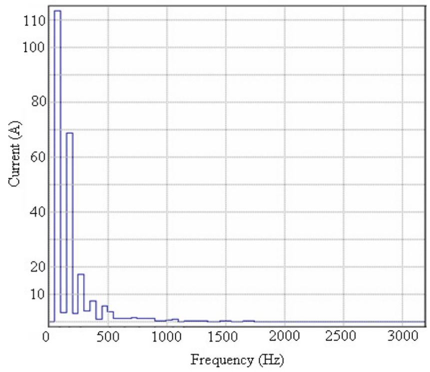
(a)



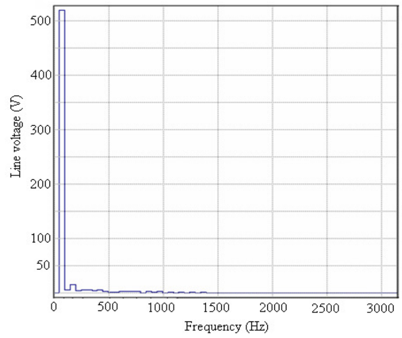
(b)

Fig. 4. Measured primary source current (a) and voltage (b) for an ESP power supply.

Measurements from Fig. 4 were made with DAQ (data acquisition card) ADA 3100 with signals conditional card, and the measurement from Fig. 5 was made with digital oscilloscope RIGOL DS 5500, after resistance divider and signal conditioning.

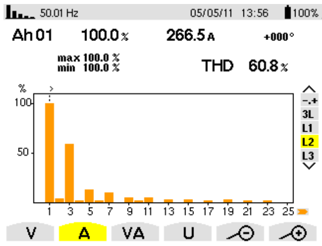


(a)

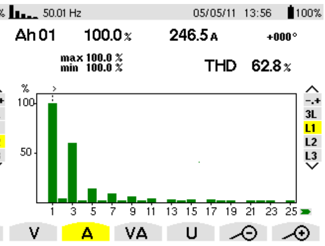


(b)

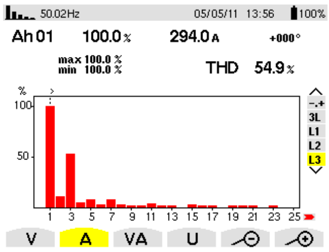
Fig. 5. Spectrum for primary source current (a) and spectrum for source voltage (b) for an ESP power supply.



(a)



(b)



(c)

Fig. 6. Spectrum of current along one minute period of time.

Measurements form Fig. 6–Fig. 8 were made with three-phase power quality analyzer CA 8334 B [15]. The spectrum of currents (Fig. 6), made along one minute (at different time), show that the dynamical operation of a section. The high order harmonic 2 to 11 exceed the maximum values accepted by standards and the total harmonic distortion (THD) of current has values between 40–77 % (Fig. 8).

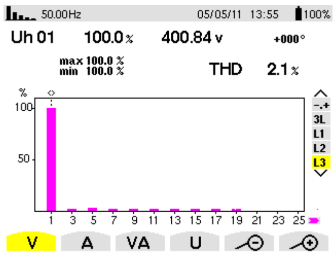


Fig. 7. Spectrum of the line voltage.

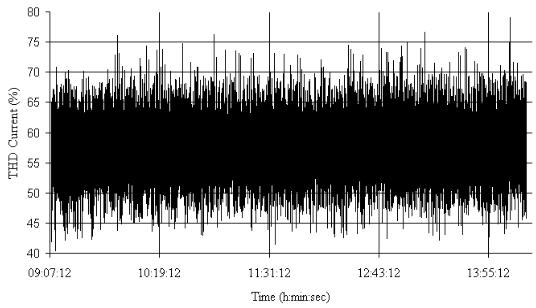


Fig. 8. THD current of ESP power supply for a few hours operation.

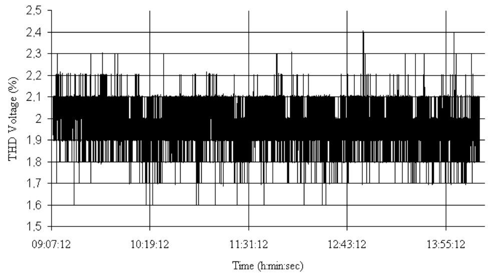


Fig. 9. THD line voltage of ESP power supply for a few hours operation.

The spectrum of voltage it is constant and has low harmonics (Fig. 7). THD voltage is below 2.4% (Fig. 9).

The values from fig 8-9 were measure with one second resolution. The section supply has nonlinear characteristics and is responsible for injecting harmonic currents and voltages into the electrical network. The direct results of harmonics cause power system problems like heating, solid-state malfunctions, and communication interference, resonance condition (especially when are use capacitor in the network) errors at measurement devices and sometime catastrophic failure [15]–[19].

IV. Simulations of a Traditional DC Energization for ESP Sections Without Passive Filter

The power supply of one ESP section was simulated with PSCAD/EMTDC using three-phase voltage source, TCR structure (Fig. 10).

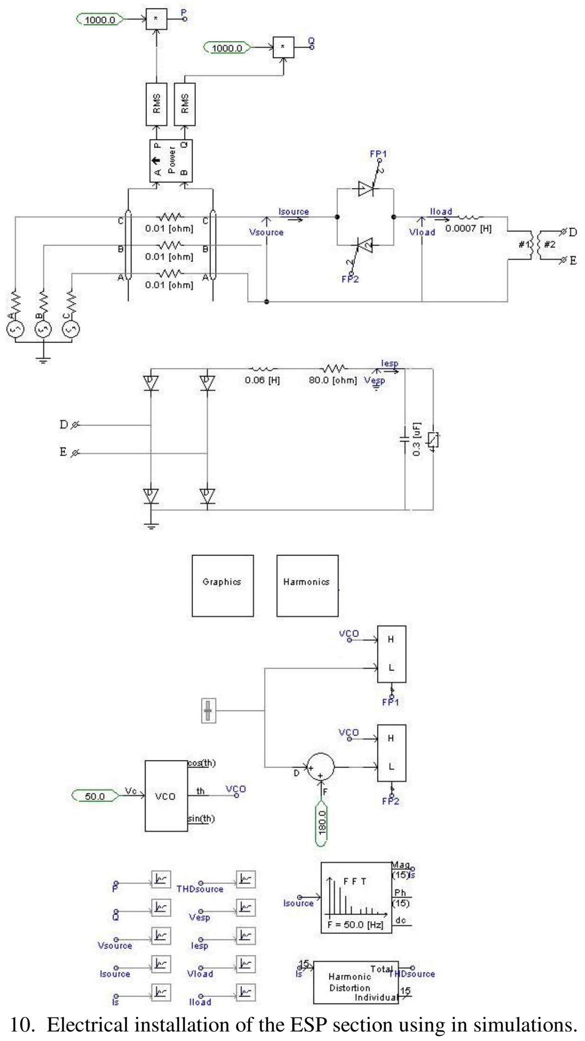


Fig. 10. Electrical installation of the ESP section using in simulations.

The firing angle α can be modify between 15...150^0. Practically, the value of firing angle α is above 45^0 and bellow 145^0. Were simulated the source voltage (V_{source}), source current (I_{source}), ESP voltage (V_{esp}), and current (I_{esp}) are simulated for different firing angle (α). With FFT block is compute the harmonic current (up to 15th harmonic) and with THD block is compute the THD current [14].

A better solution to modeling the ESP sections is to use a capacitor and measured I-V characteristic from industry ESP. The capacitor (C=0.3μF) is the electrical capacitance of the precipitator section depends on the geometrical dimensions of the sections and the dielectric proprieties of the process gases. I-V characteristic data were takes from industrial measurement of ESP with three sections (see appendix).

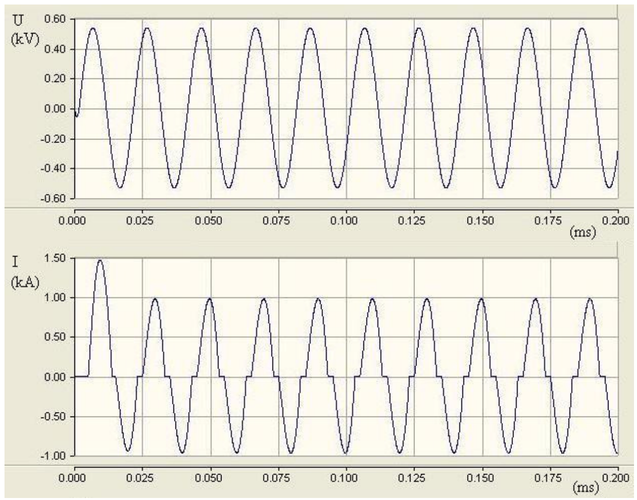


Fig. 11. Source voltage (V_{source}), source current (I_{source}), for power supply from Fig. 10, α=90^0 (THD=20.41%).

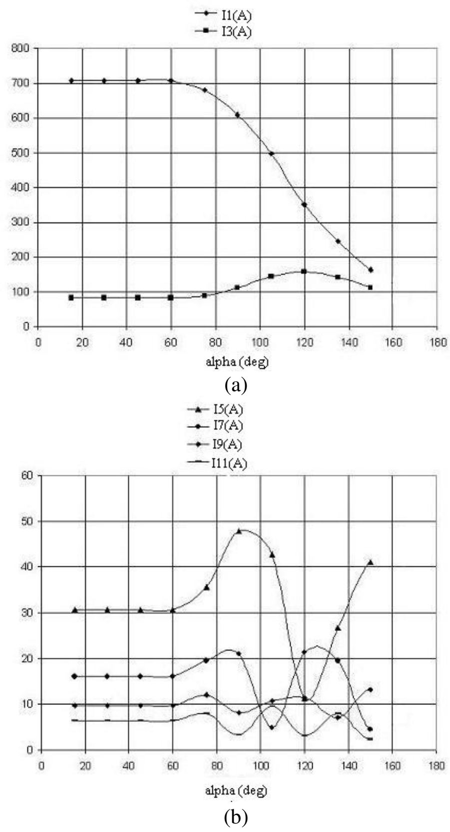


Fig. 12. Source current harmonic: a. I_1 and I_3; b. I_5, I_7, I_9, and I_{11} for α = 15...165^0.

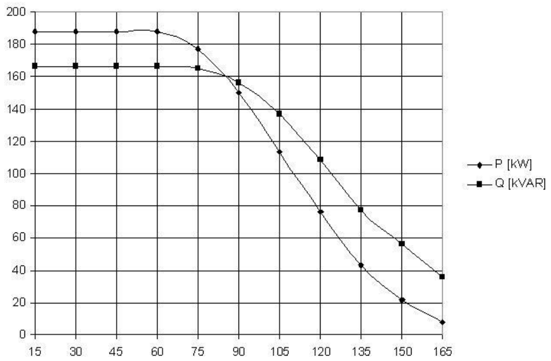


Fig.13. Effective active power (P) and effective reactive power (Q) depends on α.

V. Simulations of a Classical DC Energization for ESP Sections with Passive Filter

The power quality defects are divided into five categories: harmonic distortion; blackouts; under or over voltage; sags voltage and surges; transient phenomena. Each of these has a different cause. For example, harmonics occur into customer's own installation and may propagate into the network and affect other consumers. Harmonic can be avoid by a good design practice and well made diminish equipment. One possibility to compensate harmonic current is using the passive filters.

Passive filters have been used to diminish harmonics generated by large loads and have low cost and high efficiency. In general, passive filters have lower impedance Z_F (for a tuned harmonic frequency) than source impedance Z_S and harmonic currents flowing into the source are reduced (Fig. 14). The filter characteristics depends on impedance of the source (Z_s) and the impedance of the filters (Z_F) [12], [13].

The passive filter has the structure in Fig. 15, for 3^{rd}, 5^{rd}, 7^{rd} current harmonics and high pass filter.

The sizing of filters components for n^{th} current harmonic are made with

$$2 \cdot \pi \cdot n \cdot f \cdot L = \frac{1}{2 \cdot \pi \cdot n \cdot f \cdot C}. \quad (6)$$

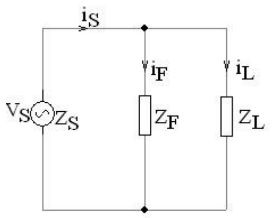


Fig. 14. Operation of passive filter.

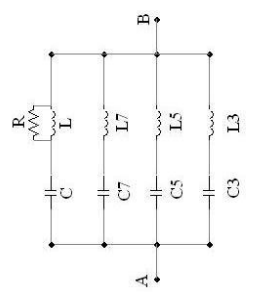


Fig. 15. Passive filter using in simulation.

TABLE I. THE VALUES OF THE PASSIVE FILTER (FIG. 15)

Harmonic order	3	5	7	High-pass filter
L[mH]	1.2	1.2	1.2	0.26
C[μF]	680	340	170	300
R[Ω]	-	-	-	3

The values of the passive filter components are give in Table I [8]. It was make simulations for electrical installation (Fig. 10) and passive filter (Fig. 15) in following situations:

- Parallel passive filter (the filter was connected in parallel with source);
- Series passive filter (the filter was connected in series with source).

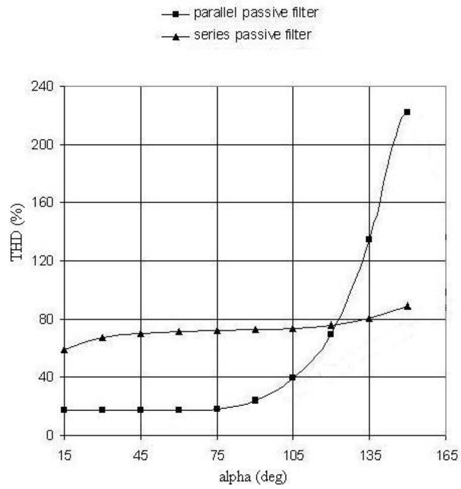


Fig. 16. THD current depends on firing angle α with passive filters.

From Fig. 16 the THD has lower values for the parallel connection of passive filters and for the firing angle lower than 120^0. The series connection of passive filter does not improve the waveforms of the currents like parallel connection of passive filter.

VI. Conclusions

Ideally, for a resistive load, the current and voltage waveforms are sinusoidal. In reality, the current in the industrial loads is not linear. An electrostatic section is a non-linear load and will produce lot of current harmonics that can be measure with modern devices and can be done rapid diagnosis and harmonic evaluation. The electrostatic sections have a dynamic operation and from this reason the current it is not constant. The THD of current modifies along of section operation. Using tuned passive filters, in parallel and series connections, the THD can be diminish bellow to 20%. Because of the dynamical operation, the active or hybrid filters may be use to achieve better waveforms of the supply current.

Appendix A

The main data using to simulations (Fig. 10):

- ESP with 3 sections;
- The high voltage transformer: 166 kVA, 0.4 kV/65 kV;
- V_{source}=400 V, 50 Hz;

- L_1=0.7 mH;
- R_2+R_a=80 Ω;
- L_2=60 mH;
- The high rectification voltage without load: 92 kV;
- The high rectification voltage with load: 47 kV;
- Gases flow: 650,000 m^3/h;
- Inlet dust concentration: 32 g/m^3_N;
- Outlet dust concentration: 0.05 g/ m^3_N;
- The gas nominal temperature: 150 ^{0}C.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Eng. Tiberiu Mircea Borca and to Eng. Vlad Florea who gave them the possibility to complete this paper.

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