Modelling of some parameters from thermoelectric power plants

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Abstract. Paper proposing new mathematical models for the main electrical parameters (active power $P$, reactive power $Q$ of power supplies) and technological (mass flow rate of steam $M$ from boiler and dust emission $E$ from the output of precipitator) from a thermoelectric power plants using industrial plate-type electrostatic precipitators with three sections used in electrical power plants. The mathematical models were used experimental results taken from industrial facility, from boiler and plate-type electrostatic precipitators with three sections, and has used the least squares method for their determination. The modelling has been used equations of degree 1, 2 and 3. The equations were determined between dust emission depending on active power of power supplies and mass flow rate of steam from boiler, and, also, depending on reactive power of power supplies and mass flow rate of steam from boiler. These equations can be used to control the process from electrostatic precipitators.

1. Introduction
Plate-type electrostatic precipitators are most commonly used in de-dusting equipment from industry. They can be used in the treatment of very large gas flows (thousands of m³/s) at different temperatures and gas pressures. It have applications in producing electricity (thermoelectric power plants), metallurgical, cement and glass industry [1].

The steam thermoelectric power plant is a chemical energy transformer in electric energy of the greatest proportions. Energy transformation can't be done directly, but through transformation of the combustion process in the heat, the heat is restored water to other the state of aggregation: liquid turns to steam with high pressure. Steam turbine drive produces such energy, mechanic, and electric generator – mechanical coupled with the turbine - transform this energy into electrical energy [2].

Fossil fuel combustion is burned in boiler absorbing oxygen from the air. Non-combustible elements from fuel remain in the form of ashes and slag (can reach 40-50% of the total fuel) boiler’s stoker, and a part will be discharged into the atmosphere. Gas with dust can't be discharged directly through the boiler due to excessive pollution which would create. For this reason, between the boiler and the funnel is installed, usually plate-type electrostatic precipitators, which collects most of the dust particles (over 95%), before being discharged to the funnel. In principle, a higher pressure steam will cause an increase in turbine speed. However, the turbine speed is kept constant, because it determines the voltage frequency made by synchronous electric generator. For maintaining constant turbine speed is used automatic adjustment installation [3], [4].

Automatic tuning system has as main task to preserve equality between power developed by turbine and generator load. The size of the informant's best of imbalance between them is the turbine...
speed. Speed controller used as the size of the execution mass flow rate of the steam in the turbine. The turbine power is directly proportional to the mass flow rate of steam and with the adiabatic drop in the turbine [5].

Mathematics modelling of parameters in the industry can be achieved with the least squares method [6-9].

Automating processes from thermoelectric power plants is important, so electricity production improvements, through various optimization processes in a power plant. Starting and stopping the filtration installations (or part of them) must be made in such way to save time, not to exceed the allowable pollution limits, and also not to affect lifetime of the facility. It must at the same time, to improve the operation of the installations, to ensure a low electricity consumption (in terms of collecting the required dust emission) and to ensure safe operation through automation [10], [11].

Precipitators with three sections are often used in industry. Each section is supplied with power from a separate voltage power source (silicon-controlled rectifier type) [3], [4]. This power source provides a high voltage in section (usually up to 60 kV) in order to create the Corona effect to produce substantial charge carriers that will attach to the dust particles from the gas. Dust particles will have the electrical charge and will collect on the surface of the collecting surface of precipitator [12].

It shows, for the case of precipitators with three sections, mathematical modelling, using the least squares method, dust emissions of precipitators (dependent parameter) depending on the total power active, reactive, and apparent power sources, and mass flow rate of steam from boiler.

2. Electrical Powers and Parameters Measurements on Precipitator Power Supplies

To measure the electrical parameters of precipitator power supplies is necessary to acquisition the voltages and currents [13].

![Figure 1. The sensors’ and probes’ connection at power quality analyser CA 8334 B at the power supplies of precipitator with three sections](image)

It is analysed a precipitator with three sections, every power supply, for each section, is connected at two phases to balance the network (Figure 1).

It is used power quality analyser (PQA), CA 8334 B (Chauvin Arnoux, France) [14]. Using PQA can be done fast Fourier transform and can be identify voltages and currents harmonics, the waveforms of voltages and currents, the total harmonic distortion, the powers (active, reactive, and apparent), and power factor [15], [16].

The high voltage in precipitator sections is generated by silicon-controlled rectifier that is connected at two phases (400 V, 50 Hz).

PQA was connected at inputs currents $C_1$, $C_2$, $C_3$, and inputs voltages $V_1$, $V_2$, $V_3$, for each power supply using one current sensor ($CT$) AmpFLEX (current measuring up to 3000 A), and one two line low voltage probes ($L_1$, $L_2$ or $L_2$, $L_3$ or $L_3$, $L_1$) [15]. Because precipitator has three sections the PQA
was connected like in Figure 1 using three current sensors (CT₁, CT₂, CT₃) and three line low voltage probes (L₁, L₂, L₃). The current sensors are connected on the aluminium bus bars, in front of fuses and circuit breaker, to measure the electrical parameters.

Some specific electrical measurements for deforming state are given below [6], [13], [17]. In reality, each of the periodic signals (currents, voltages) has an infinite number of harmonics. From the practical point of view, to be able to accomplish calculations by PQA, the maximum number of harmonics to be taken into account is, in most cases, 40. In relationships (1) to (4), k is degree harmonics and with 0 is indicated continuous component.

The root-mean square (RMS) of current is:

\[ I = \sqrt{I₀² + \sum_{k=1}^{40} I_k²} , \]  

and, the root-mean square of voltage is:

\[ U = \sqrt{U₀² + \sum_{k=1}^{40} U_k²} . \]  

If it makes \( \varphi \) the phase displacement between voltage and current, for each of harmonics, the active power in un-sinusoidal is defined as:

\[ P = U₀ \cdot I₀ + \sum_{k=1}^{40} U_k \cdot I_k \cdot \cos \varphi_k , \]  

and, the reactive power is:

\[ Q = \sum_{k=1}^{40} U_k \cdot I_k \cdot \sin \varphi_k . \]  

Apparent power can be determined according to the root-mean square of the voltage and current:

\[ S = U \cdot I . \]  

In deforming state, it is used another specific power, namely the deform power:

\[ D = \sqrt{S² - (P² + Q²)} . \]  

In Figure 2 is the Fresnel diagram, for voltages and currents fundamentals (at 50 Hz), in the case of the three sources of the sections. With the indexes 1,2 and 3 it is noted the source’s phases (like in Figure 1). From the diagram it can be seen the symmetrical and balanced voltage, as well as the inductive nature of loads (the current is after the voltage).

\[ Figure 2. \] Fresnel diagram for fundamental currents and voltages for power supplies

The power sources have the two thyristors connected in anti-parallel, which are control by firing angle. A higher value of the firing angle dues a lower root mean square of voltage. In this way, it can
change the voltage in the rise-up transformer, and in the secondary winding where is connected the precipitator’s section.

In Figure 3, for a power supply (behaviour is the same for the other two power sources) are present the voltage and the current absorbed by the network. Due to the principle of the operating of the silicon-controlled rectifier power sources, the supply voltage is sine (measured frequency, f = 50.02 Hz), but the current is not the sine shape and will introduce a deforming state. The deforming state of the power sources can be highlighted in Fig. 4 where it shows the analysis of harmonic currents in the three phases (L₁, L₂, L₃).

Thanks to automatic voltage adjustment in sections (due to the events into sections), the \textit{RMS} voltage in the primary winding transformer changing every time, and also, the \textit{RMS} value and the shape of the current absorbed by the network.

**Figure 3.** Current and voltage on phase L₁ for input section power supply for one period of time (20 ms)

**Figure 4.** Spectrum analysis of currents through phases L₁, L₂, and L₃ at one moment of time

**Figure 5.** Mass flow rate of steam M depending on time for the boiler that is connected at the input of precipitator with three sections

From this reason, the spectrum currents are changing permanently.

The mass flow rate of steam generated by the boiler, is not constant (for various reasons, i.e.: the type of fuel, the type of burning of fuel, the generator loading), but is stored in certain limits. Figure 5 shows the evolution of the typical mass flow rate of steam over the course of several hours.
The dust emission at the output of the precipitator with three sections, it is not constant (for various reasons, i.e.: type of power sources, type of current control, burning type, the generator loading). A typical evolution over the course of a few hours of operation is shown in Figure 6. Regardless of the factors that influence the performance of the precipitator collection, it must remain within the limits of design in terms of dust emissions (smaller than the designed value).

3. Mathematical Modeling through Least Squares Method

Let consider the mathematical function that will model the measure data:

$$z = f(x, y, a_0, a_1, a_2, ..., a_n),$$

where $z$ is the variable dependent, and $x, y$ are the independent variables, and index $t$ represents theoretical values. $x, y$, and $z$ are electrical and/or technological parameters, and $a_0, a_1, a_2, ..., a_n$ are the coefficients of the function that will be determined. The number of these coefficients depend on the type of function used (i.e., polynomial function of some degree; basically, it can use a function of 2nd or 3rd degree) [6], [7].

A criterion of choice of optimal mathematical model is that of the minimum sum of squares of deviations from the theoretical function compare with real data (made by measurements) which is called the least squares method:

$$F = \sum_{k=1}^{n} \varepsilon_k^2 = \sum_{k=1}^{n} (z_{mk} - z_k)^2 = \sum_{k=1}^{n} [z_{mk} - f_i(x_{ik}, y_{ik}, a_0, a_1, a_2, ..., a_n)]^2,$$

where, $F$ is the sum of squares of deviations $\varepsilon_k^2$, index $k$ is order number of measuring data, index $n$ is number of measuring data, and index $m$ represents measured values. Mathematical modelling is considered by this method when the function $F$ from Eq. (8) is minimal:

$$F = F_{\text{min}}.$$

For the determination of the coefficients of function $(a_0, a_1, a_2, ..., a_n)$, the system of equations must be solved:

$$\frac{\partial F}{\partial a_0} = 0; \frac{\partial F}{\partial a_1} = 0; \frac{\partial F}{\partial a_2} = 0; ... \frac{\partial F}{\partial a_n} = 0,$$

and, after solving, the coefficients $a_0, a_1, a_2, ..., a_n$ are replace in Eq. (8).

It defined two parameters, used in statistics, which are used in this method. The root-mean square deviation ($R_{\text{MSD}}$) is:

$$R_{\text{MSD}} = \sqrt{\frac{1}{n} \sum_{k=1}^{n} [z_{mk} - f_i(x_{ik}, y_{ik}, a_0, a_1, a_2, ..., a_n)]^2}.$$

If $R_{\text{MSD}}$ is smaller, with the theoretical function $f_i$ modelled better the real measured data.

The correlation coefficient ($\rho$) can be compute with:
\[
\rho = \sqrt{1 - \frac{n \sum_{k=1}^{n} (z_{mk} - \overline{z}_m f_1(x_{tk}, y_{tk}, a_0, a_1, a_2, \ldots, a_n))^2}{\sum_{k=1}^{n} (z_{mk} - \overline{z}_m)^2}},
\]

(12)

where \( \overline{z}_m \) represents the average values of data:

\[
\overline{z}_m = \frac{1}{n} \sum_{k=1}^{n} z_{mk}.
\]

(13)

Correlation coefficient represents the intensity of dependence among the parameters (dependent and independent), and can has values between 0 and 1. A value of \( \rho \) nearby 1 value indicates a direct connection between the parameters, meaning a growth of independent parameters determines increasing of dependent parameter.

Mathematical modelling has been used measured data (Table 1) from an industry precipitator (the main data in the appendix) from S.C. Electrocentrale Deva S.A. (thermoelectric power plant), Romania. In Table 1, \( P \) – total active power, \( Q \) – total reactive power, \( S \) – total apparent power (\( P, Q, S \) are sums for all three power sources), \( M \) - flow rate of steam from boiler, and \( E \) – dust emission at the output of precipitator.

**Table 1. Measurement parameters used at mathematical modelling**

| No. | P  (kW) | Q  (kVAR) | S  (kVA) | M  (t/h) | E  (mg/m³) |
|-----|---------|-----------|----------|----------|------------|
| 1   | 103.11  | 181.91    | 209.86   | 286.47   | 397.58     |
| 2   | 112.45  | 184.46    | 215.97   | 279.85   | 404.29     |
| 3   | 124.02  | 190.65    | 227.57   | 280.95   | 431.81     |
| 4   | 104.93  | 178.05    | 207.29   | 285.73   | 406.98     |
| 5   | 117.89  | 179.43    | 214.95   | 302.64   | 445.9      |
| 6   | 108.61  | 171.16    | 203.29   | 287.2    | 398.92     |
| 7   | 137.91  | 192.85    | 237.11   | 284.63   | 409.66     |
| 8   | 111.29  | 170.51    | 204.1    | 283.89   | 412.34     |
| 9   | 115.9   | 179.85    | 214.22   | 284.26   | 434.15     |
| 10  | 120.68  | 177.15    | 214.76   | 302.64   | 448.59     |
| 11  | 120.33  | 179.28    | 216.55   | 280.22   | 425.1      |
| 12  | 112.21  | 171.55    | 205.97   | 285.73   | 396.24     |
| 13  | 110.45  | 168.21    | 201.81   | 278.01   | 412.34     |
| 14  | 109.27  | 164.67    | 198.42   | 282.42   | 433.15     |
| 15  | 117.55  | 164.08    | 202.53   | 287.94   | 399.59     |
| 16  | 129.17  | 175.11    | 217.6    | 279.11   | 419.73     |
| 17  | 118.01  | 169.34    | 206.95   | 280.95   | 402.28     |
| 18  | 123.4   | 163.99    | 205.51   | 283.16   | 397.58     |
| 19  | 127.73  | 165.96    | 209.83   | 277.64   | 407.65     |
| 20  | 119.14  | 162.45    | 201.54   | 303.75   | 449.93     |
| 21  | 119.3   | 165.72    | 204.89   | 286.47   | 403.62     |
| 22  | 130.5   | 175.69    | 218.93   | 289.41   | 421.74     |
| 23  | 123.07  | 170.24    | 210.21   | 285     | 396.24     |
| 24  | 125.44  | 170      | 211.3    | 293.08   | 429.12     |
| 25  | 127.82  | 160.83    | 205.62   | 298.23   | 439.19     |
It was determined the mathematical modelling through least squares method for \( E = f(M,P) \), with three types of equations: 1\textsuperscript{st} degree equation Eq. (14) and Figure 7, 2\textsuperscript{nd} degree equation Eq. (15) and Figure 8, and 3\textsuperscript{rd} degree equation Eq. (16) and Figure 9.

The regression’s equation for 1\textsuperscript{st} degree equation is:

\[
E = 0.365 \cdot P + 1.413 \cdot M - 31.704 .
\]  

(14)

\[ \text{Figure 7. Dust emission } E \text{ depending on mass flow rate of steam } M \text{ and active power } P, \text{ mathematical modelling 1}^{\text{st}} \text{ degree equation} \]

The regression’s equation for 2\textsuperscript{nd} degree equation is:

\[
E = -0.005 \cdot P^2 + 0.09 \cdot P \cdot M + 0.135 \cdot M^2 - 24.35 \cdot P - 87.788 \cdot M + 14397.975.
\]  

(15)

\[ \text{Figure 8. Dust emission } E \text{ depending on mass flow rate of steam } M \text{ and active power } P, \text{ mathematical modelling 2}^{\text{nd}} \text{ degree equation} \]

The regression’s equation for 3\textsuperscript{rd} degree equation is:

\[
E = -0.001 \cdot P^3 - 0.006 \cdot P^2 \cdot M + 0.006 \cdot P \cdot M^2 + 0.01 \cdot M^3 + 2.318 \cdot P^2 - 2.1 \cdot P \cdot M - 9.2 \cdot M^2 + 3.939 \cdot P + 2743.301 \cdot M - 259231.362.
\]  

(16)
Figure 9. Dust emission $E$ depending on mass flow rate of steam $M$ and active power $P$, mathematical modelling $3^{rd}$ degree equation

Table 2. The root-mean squares deviations and correlations coefficients for $E = f(M,P)$

| No. | 1$^{st}$ degree equation $R_{MSD}$ (mg/m$^3$) | 2$^{nd}$ degree equation $R_{MSD}$ (mg/m$^3$) | 3$^{rd}$ degree equation $R_{MSD}$ (mg/m$^3$) |
|-----|----------------------------------|----------------------------------|----------------------------------|
|     | 13.157                           | 10.672                           | 10.43                            |
|     | 0.651                            | 0.788                            | 0.799                            |

The root-mean square deviations and correlations coefficients are presented for the three cases (Eqs. (14), (15), (16)) in Table 2. The best mathematical modelling is made with $3^{rd}$ degree equation. The lower deviation and the greatest correlation coefficient are for $3^{rd}$ degree equation.

Root mean square deviation $R_{MSD}$ measure the differences between values predicted by a model or an estimator and the values actually measured. $R_{MSD}$ is a good measure of accuracy. These individual differences are called residuals, and $R_{MSD}$ serves to unit them into a single measure of predictive power. Correlation coefficient $\rho$ is a quantity that gives the quality of a least squares fitting to the measure data [6]. The burning of a large coal amounts, due a greater mass flow rate of steam ($M$) and higher dust emissions ($E$). With increasing amounts of dust is required a greater amount of active power of supplies (Figures 7-9).

In Table 3, are given the minimum, average and maximum $P$, $Q$, $S$, $M$ and $E$ sizes measured.

Table 3. Measure minimum, average, and maximum values $P$, $Q$, $S$, $M$ and $E$

| No. | $P$ (kW) | $Q$ (kVAR) | $S$ (kVA) | $M$ (t/h) | $E$ (mg/m$^3$) |
|-----|----------|------------|-----------|-----------|---------------|
| Minimum | 103.11 | 160.83 | 198.42 | 277.6 | 396.24 |
| Average | 118.81 | 173.32 | 210.67 | 286.8 | 416.95 |
| Maximum | 137.91 | 192.85 | 237.11 | 303.8 | 449.93 |

Regression hypersurface equation $E=f(M,P,Q)$ is:

$$E = -0.029 \cdot P^2 - 0.024 \cdot Q^2 + 0.131 \cdot M^2 + 0.03 \cdot P \cdot Q - 0.036 \cdot Q \cdot M + 0.104 \cdot M \cdot P - 27.939 \cdot P + 15.817 \cdot Q - 80.949 \cdot M + 12217.273.$$  \hspace{1cm} (17)

For Eq. (17) $R_{MSD}=9.736$ and $\rho=0.827$ (that indicates a better correlation between parameters $E,M,P,Q$). The stationary point is a stable area of operation, where the parameters change little (their derivatives tend to 0). Coordinates of stationary point for Eq. (17) are: $M=284.146$ t/h, $P=130.585$ kW, $Q=193.01$ kVAR, $E=418.885$ mg/m$^3$.

From Eq. (17) results Eqs. (18), (19) and (20). To three-dimensional representation, the third independent parameter $M$, $P$, or $Q$, the average value is used. In Figures 10-12 show the dependencies
In the Eq. (18) and Figure 10 was presented $E=f(M, P, Q)$ for $P_{\text{avg}}$, in the Eq. (19) and Figure 11 was presented $E=f(P, M)$ for $Q_{\text{avg}}$, and in the Eq. (20) and Figure 12 was presented $E=f(P, Q)$ for $M_{\text{avg}}$.

$$E = 0.024 \cdot Q^2 + 0.131 \cdot M^2 - 0.036 \cdot Q \cdot M + 19.45 \cdot Q - 68.5679 \cdot M + 8493.276$$

(18)

Figure 10. Dust emission $E$ depending on mass flow rate of steam $M$, reactive power $Q$, and average active power $P_{\text{avg}}$, mathematical modelling 2nd degree equation

$$E = 0.131 \cdot M^2 - 0.029 \cdot P^2 + 0.104 \cdot M \cdot P - 87.301 \cdot M - 22.718 \cdot P + 14232.135$$

(19)

Figure 11. Dust emission $E$ depending on active power $P$, mass flow rate of steam $M$, and average reactive power $Q_{\text{avg}}$, mathematical modelling 2nd degree equation

High dust emissions are influenced the most by increasing the mass flow rate of steam, and implicit, a larger quantity of burning coal. With increasing of dust emissions, increases, also, reactive power sources.

$$E = -0.029 \cdot P^2 - 0.024 \cdot Q^2 + 0.03 \cdot P \cdot Q + 1.948 \cdot P + 5.306 \cdot Q - 228.09$$

(20)
Figure 12. Dust emission $E$ depending on reactive power $Q$, active power $P$, and mass flow rate of steam $M_{\text{avg}}$, mathematical modelling 2nd degree equation

Higher dust emissions due growth of active and reactive powers, up to a certain value (Figure 12). The evolutions of active and reactive power are due by type of power sources and the control current inside sections. With increasing of dust emissions should increase powers.

Regression hypersurface equation $E=f(M,P,S)$ is:

$$
E = -0.06 \cdot P^2 - 0.04 \cdot S^2 + 0.131 \cdot M^2 + 0.081 \cdot P \cdot S - 0.048 \cdot S \cdot M + 0.131 \cdot M \cdot P - 40.017 \cdot P + 21.428 \cdot S - 80.219 \cdot M + 11941.467. 
$$

For Eq. (21) $R_{\text{MSE}}=9.727$ and $\rho=0.828$ (that indicates a better correlation between parameters $E,M,P,S$). Coordinates of stationary point for Eq.(21) are: $M=284.203$ t/h, $P=130.386$ kW, $S=231.954$ kVA, $E=418.677$ mg/m$^3$. The stationary point coordinates are in graphical limits.

From Eq. (21) results Eqs. (22), (23), (24). For three-dimensional representation, the third size $M$, $P$, or $S$, is used as an average value. In Figures 13-15 are presented the dependency $E=f(M,P,S)$. In the Eq. (22) and Figure 13 was presented $E=f(M,S)$ for $P_{\text{avg}}$, in the Eq. (23) and Figure 14 was presented $E=f(P,M)$ for $Q_{\text{avg}}$, and in the Eq. (24) and Fig. 15 was presented $E=f(P,S)$ for $M_{\text{avg}}$.

$$
E = -0.04 \cdot S^2 + 0.131 \cdot M^2 - 0.048 \cdot S \cdot M + 31.045 \cdot S \cdot 64.752 \cdot M + 6334.347
$$

Figure 13. Dust emission $E$ depending on mass flow rate of steam $M$, apparent power $S$, and average active power $P_{\text{avg}}$, mathematical modelling 2nd degree equation

$$
E = 0.131 \cdot M^2 - 0.06 \cdot P^2 + 0.13 \cdot M \cdot P - 90.308 \cdot M + 22.964 \cdot P + 14698.23
$$
Figure 14. Dust emission $E$ depending on active power $P$, mass flow rate of steam $M$, and average apparent power $S_{avg}$, mathematical modelling 2nd degree equation

$$E = -0.06 \cdot P^2 - 0.04 \cdot S^2 + 0.08 \cdot P \cdot S - 2.685 \cdot P + 7.693 \cdot S - 305.181$$

(24)

Figure 15. Dust emission $E$ depending on apparent power $S$, active power $P$, and average mass flow rate of steam $M_{avg}$, mathematical modelling 2nd degree equation

High level of dust emissions determines the increasing of apparent power and active power (up to a certain value) of power sources (Figure 15).

4. Conclusions
Using PQA complete data acquisition of main data can be made. It can be acquire the data through a period of time in normal and transient mode operation of industrial precipitators from thermoelectric power plants.

To establish a mathematical model of a dependent parameter on other parameters, it can use the least squares method, which establishes minimum sum of square deviations for a certain mathematical function.

For a precipitator with three sections establishes the evolution of dust emissions depending on the amount (for the all three power sources) of active, reactive, and apparent powers, and depending on the mass flow rate of steam from boiler.

It was found that the mass flow rate of steam from boiler influences the most dust emissions. The levels of active, reactive, and apparent powers depend on the type of power sources and the type of control current inside the section.

Appendix
The main data of precipitator:
- Precipitator with three sections;
The rise-up transformer: $S=166 \text{kVA, } 0.4\text{kV}/65\text{kV}$;
- Network voltage: $V_{\text{source}}=400 \text{V, } 50 \text{ Hz}$;
- The maximum high rectification voltage: $V_{\text{ESPmax}}=92 \text{kV}$;
- The rated high rectification voltage: $V_{\text{ESP}}=60 \text{kV}$;
- Gases flow: $F=650,000 \text{ m}^3/\text{h}$;
- Maximum design output dust emission $q_{\text{out}}=750 \text{ mg/m}^3\text{N}$;
- The gases nominal temperature: $t=150 \text{ }^\circ\text{C}$.

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