Modern High-Voltage Control of an Electrostatic Precipitator

Herman Mooij
Eon-Benelux
Netherlands
Herman.Mooij@
eon-benelux.com

Dr. Manfred Schmoch
Steinmüller-Engineering
Germany
Manfred.Schmoch@
siemens.com

Dr. Josef von Stackelberg
Rico-Werk
Germany
j.vonstackelberg@
rico-werk.com

1 Summary / Abstract:

A modern high-voltage control of an electrostatic precipitator provides both high separation efficiency and low demand of electrical power. The paper explains the physical background how this pretended contradiction can be dissolved. Motivation for this contribution is the convincing result of an electrical ESP retrofit behind the bituminous coal fired boiler in Maasvlakte / Netherlands.

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2 Introduction

Dry electrostatic precipitators have been used in various industries for decades and precipitate dust reliably. They contain relatively few wear parts which are replaced at intervals of several years. Since the high voltage transformers and control systems contain no moving parts, they are practically maintenance free over the entire period.

The new requirements for lower clean gas dust content values and the poor availability of spare parts for the old control systems support the idea of replacing the old control system with a modern digital one.

Modern control systems provide new opportunities for achieving more effective dust precipitation:

- They use more precise, differentiated, and faster analysis methods.
- This allows them to adjust the voltage to the individual conditions more precisely and at a higher level.
- In particular, knowledge about the physical processes involved in dust precipitation can be used to achieve targeted current and voltage control based on various criteria. Voltage control can also be coordinated with other processes in the filter, such as rapping.

To understand the additional opportunities provided by modern digital control systems, it is first necessary to describe some of the physical aspects affecting dust precipitation.

3 Physical aspects of dust precipitation

The raw gas flow with a high dust content flows into the active filter space, which is divided into numerous lanes. Each of the lanes is terminated at a height of ~16 m by metal plates, the grounded collecting electrodes on which a layer of dust agglomerates.

In the centre between the collecting electrodes, discharge electrodes release electrons through the corona effect. These electrons combine with the gas molecules to form negative gas ions (Fig. 1; diagram according to /1/).

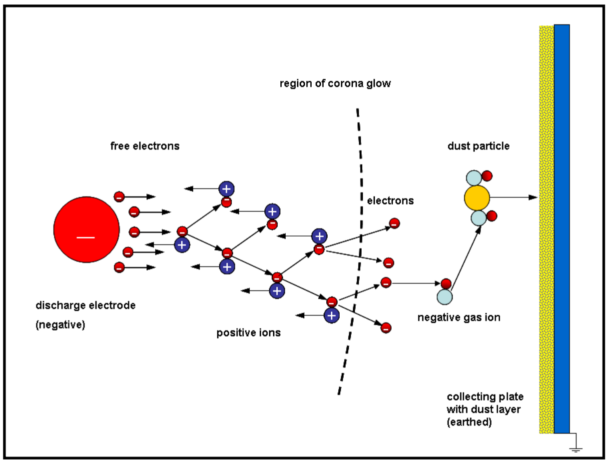

Fig. 1: Particle charging via the negative corona according to /1/

Some of these gas ions attach to the dust particles in the gas flow. The other – usually significantly larger – portion flows directly to the dust layer under the effect of the electrical field, passes through the dust layer, and discharges into the collecting electrode.

The same electric field effect also causes the electrically charged dust particles to drift towards the collecting electrode. Due to their relatively large mass, the dust particles travel much slower than the gas ions. The dust particles collect on the collecting electrode and form a layer of dust. The charge they collected in the form of attached gas ions travels through the dust layer to the grounded electrode and is discharged.

All charges, those coming directly from the discharge electrode and those carried on the dust particles, generate the electrostatic forces which hold the dust onto the collecting electrode plate and cause it to agglomerate into a compact layer.

Dust precipitation is most effective when the electrical field strength between the discharge and collecting electrodes is highest. Increased field strength

- increases the potential charge on the individual dust particles (fig. 2) and
- increases the force which drives each charged particle towards the collecting electrode.

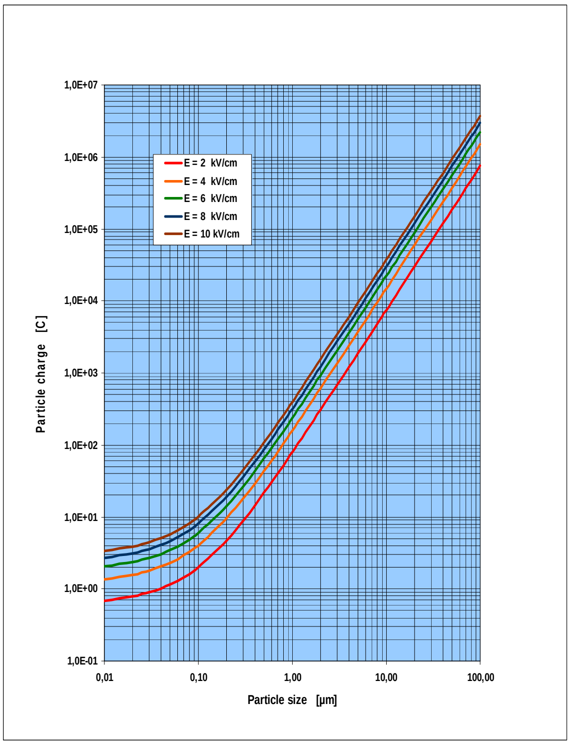

Fig. 2: Saturation charge versus the field strength on the particle

So the drift speed is increased disproportionately by increasing the force per charge and by increasing the number of charges with higher electrical field strengths. Therefore the main goal of the high voltage control system is to maintain a maximum voltage as close to the disruptive discharge point as possible.

Even though the gap between the discharge and collecting electrodes only contains gas and dust consisting of nonconducting materials, a small current flows in the electrostatic precipitator anyway due to the corona. Similar to conducting systems, the system consisting of "discharge electrode – gas lane – dust layer - collecting electrode" can be modelled as a series of electrical resistors. Similarly, the individual electrical resistances determine the voltage ratios which are established in order to allow a certain amount of current to flow between the discharge and collecting electrodes. The effects of this relationship are described in figures 3 and 4:

The graphs 1 through 4 in fig. 3 show U,I response curves for a series of tests, for which the discharge point is located 12.5 mm in front of a plate acting as collecting electrode. This design, quoted from /1/, only corresponds to the situation in an electrostatic filter in principle. Therefore the absolute values are different from the familiar magnitudes in an electrostatic precipitator. However, the physical phenomena are the same and can be observed very clearly.

The gas lane between the electrodes is free from dust, but the collecting electrode is covered by varying amounts of dust.

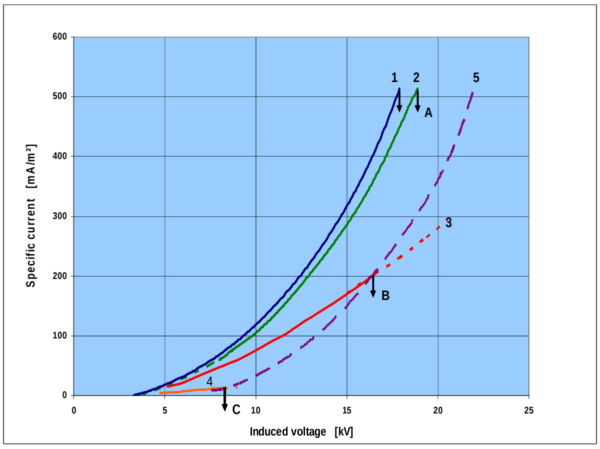

Fig. 3: U, I characteristic curve in relation to the specific dust resistance /1/

- Curve 1: No-load characteristic curve without dust; Current I_1; Field strength E_{dust1} = 0 kV/cm
- Curve 2: 2 mm dust; specific resistance = 10^8 Ω cm; $I_2 \approx I_1$; E_{dust2} > 0 kV/cm
- Curve 3: 2 mm dust; 109 Ω cm; I3 < I2; Edust3 ≈ Ecrit ≈ 20 kV/cm
- Curve 4 2 mm dust; 1010 Ω cm; I4 < I3; Edust4 ≈ Ecrit ≈ 20 kV/cm
- Curve 5 marks the line at which a field strength of Ecrit = 20 kV/cm develops above the dust layer – depending on the current and resistance of the dust layer and on the current applied to the discharge electrode.

The dielectric strength of the gas layer for this electrode configuration – without dust – can be read on curve 1. The field strength at the discharge electrode is the limiting factor for the maximum voltage setting. (see also /1/, chapter 7.1).

Since the current in the dust layer for curve 2 requires a higher voltage than in the gas layer with the same dielectric strength in order to flow, the voltage level rises a bit. For approximately the same current, the field strength at the discharge electrode is once again the limiting factor (point A); the field strength in the dust layer is not critical.

The gas-containing dust layer can withstand a field strength of approx. 20 kV/cm (curve 5) before disruptive discharge occurs. The fact that curve 3 is flatter shows that the higher resistance of this dust layer means that a higher voltage is required for the same current to flow through an equally thick layer as in curves 1 or 2.

Therefore the field strength rises quickly, already reaching the critical value (point B) and disruptive discharge at low current values. The dashed part of the curve corresponds to the options for the gas layer, but cannot be shown due to the limiting properties of the dust layer.

Curve 4, for which the dust resistance is even higher (point C), illustrates an even more extreme situation.

When disruptive discharge of the dust layer occurs, its electric resistance collapses to a very small value. Therefore the entire voltage between the electrodes is suddenly applied across the gas layer, when it was previously distributed between the gas layer and the dust layer. Depending on the voltage level, this change to the system has different effects:

- If the voltage between the electrodes after the disruptive discharge is near (curve 3, point B) or above the maximum voltage of the no-load characteristic curve (curve 1), then the disruptive discharge across the dust layer "ignites" the gas layer: Sparking occurs across the entire distance.

- If the resistance of the dust layer is very high, the electric load on the gas layer remains low; backionisation occurs: The sparking points of the dust layer remain stable. The arc causes partial disintegration of the agglomerated dust layer. Discharge electrode feedback causes the current to rise while the voltage remains constant. Controlled precipitation and agglomeration of the dust is no longer ensured.

This understanding of the dependencies resolves several apparent contradictions of observed filter operation and affects the strategy used for optimal operation of an electrostatic precipitator.

Example: In power plants fired with lignite or bituminous coal and in many other applications, experience has shown that the precipitation performance improves as the steam content in the flue gas increases. Higher gas humidity values allow the high voltage control system to set higher current and voltage values.

But the dielectric strength of a gas drops as the humidity increases, e.g. /2/!

Apparently the resistance in the dust layer is decreased significantly, therefore allowing higher currents to flow at tolerable voltage ratios. The dielectric strength of the gas layer drops at a comparatively slower rate; critical voltages for the gas layer are not yet exceeded.

In a non-conductor system, charges move at very different speeds at different field strengths and resistances; the differences are much more apparent than in a conducting system.

At the same electric field strength, the charges move more slowly in a medium with high resistance than in one with a lower resistance. This difference in speed results in localized differences in charge concentration within the dust layer. The voltage required for the applied constant current (= charge/time) to flow develops through this difference in concentration. In the end, the different speeds of the charges lead to very different behaviour in the system components - discharge electrode, gas layer, dust layer, and collecting electrode - over time.

If the voltage applied to an electrostatic precipitator is switched off suddenly, the excessive charges at the discharge electrode and in the gas layer are dissipated within milliseconds (fig. 4). But this process takes on the order of tenths of seconds or even seconds in the dust layer: the time increases with the resistance of the dust layer.

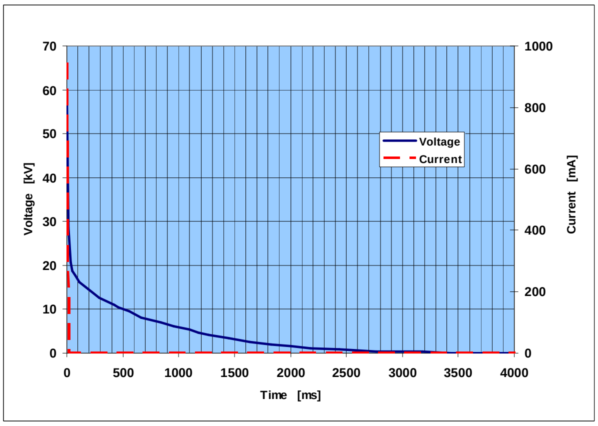

Fig. 4: Dissipation of the charge on the discharge electrode after the high voltage supply is switched off

Fig. 4 shows a test during which a high-voltage unit is switched off during operation. The tested filter removes very fine dust with a relatively high resistance rating. The current which is applied to the discharge electrode as a charge supply was measured. This value drops to zero almost immediately after the supply is switched off.

As the voltage measured between the discharge and collecting electrodes drops, a current also flows in order to discharge the discharge electrode. But this current cannot be measured by the ammeter in the high voltage unit! If the voltage across the dust layer is well above the corona discharge voltage, then discharging of the discharge electrode occurs very quickly and ends when the corona discharge voltage – approx. 20 kV in this case – is reached. As the charge in the dust layer slowly discharges into the collecting electrode, this also causes the voltage across the dust layer to fall which pulls the corona discharge voltage down as well: a small amount of current flows from the discharge electrode again. So the delayed discharge of the discharge electrode is due to the slow discharge of the dust layer.

In fact, the dust layer discharges even more slowly than the diagram in fig. 4 suggests. Because in parallel with the discharge current, some of the current also flows through the measuring resistors and the protective resistor of the high voltage unit, a process which only becomes significant for the slow processes. This also allows the voltage at the discharge electrode to fall to zero. Otherwise it would remain just below the corona discharge voltage for a clean collecting electrode.

All of these physical phenomena should be incorporated into the strategy for effective dust precipitation.

4 Requirements for the high voltage control system

A modern high voltage control system used to remove dust with a relatively high specific electric resistivity in a dry electrostatic precipitator must meet the following criteria:

- Analysis of the current and voltage values over time should be as highly differentiated as possible, with a resolution of milliseconds.
- The control measures resulting from the analysis are also determined within milliseconds. Control steps are taken as quickly as possible and at the right time. This means that the control signal on the primary side of the transformer must take effect on the secondary side as quickly as possible. The desired time here is also less than one millisecond.
- The control system must be able to adjust automatically to dust with varying electrical resistivity values.
- The control system should allow for the use of different strategies for different types of dust. Examples include aiming for minimum gas dust content values or setting the lowest possible power input in order to achieve specified gas dust content values.
- The control system should coordinate the supply voltage and rapping for the individual electric fields of a filter according to the dust quality.

4.1 Arcs, bursts

Arcs are discharge events which continue as long as the supply of electrical energy from the grid is not interrupted. They are only extinguished after the energy supply is interrupted and after a cooldown phase (50 … 100 ms).

The primary task of the high voltage control unit is to detect and quench an arc within milliseconds. The quenching time and therefore also the no-voltage time is not given by the control system, but is based on the physical conditions in the filter.

Arcs must be recognized accurately in order to avoid unnecessary shutdown of the electric field.

Bursts are discharge events during which the charge in the filter zone is discharged within milliseconds. But the dielectric strength is restored within a few milliseconds on its own and the electric field remains almost stable (fig. 5).

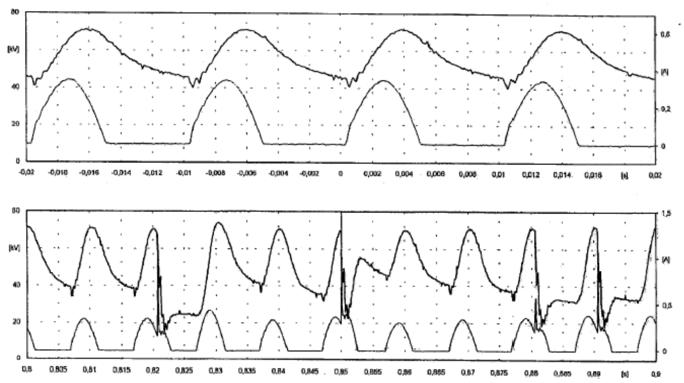

Fig. 5: Detecting a burst as a self-quenching discharge and "ignoring" the event

Triggering a quenching period is therefore unnecessary. This event must also be detected with a high degree of precision and differentiated from an arc.

4.2 Operation for precipitating dust with a high electrical resistance

The described electrical relationships for precipitating dust with a high electrical resistance result in the following requirements for the control system:

- The current must be limited.
- Nevertheless, the attained voltage and field strength should be as high as possible.
- The conditions in an electric field should be as homogenous as possible: Either an equally thick dust layer everywhere or, at the other extreme: no dust layer anywhere.

While the requirements of limited current and maximum voltage are contradictory, it is possible to approach them more closely by taking advantage of the different behaviour of the discharge electrode and the dust layer in time. Millipulsing was already used in the 80s in order to counter the fixed relationship between the field strength at the geometrically fixed discharge electrode and the discharged corona current by taking advantage of the different time behaviour, especially with regard to the discharge electrode and the dust layer. (Fig. 6).

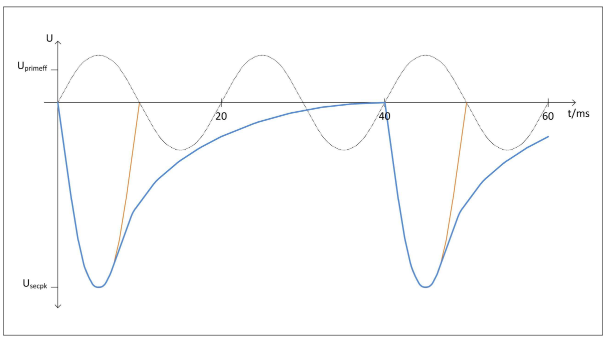

Fig. 6: Current and voltage progression during millipulsing: The time period shown is 60 ms; the dotted sine curve shows the primary voltage, the brown line the DC pulse voltage; the slow decay of the secondary voltage after the pulse can be seen clearly (blue line); a 1-3 pulse ratio is shown

Practical experience has shown that this method of voltage control provides better dust precipitation results than the method described above, where the current and voltage are reduced to the minimum permissible current. At the maximum voltage for the gas layer, the amount of applied charge can still be absorbed by the dust layer without a disruptive discharge. Turning off several half cycles provides the necessary wait time required by the dust layer to dissipate the charge to the collecting electrode. This amount of charge is supplied again by the following active half cycles, preferably at a voltage determined by the dielectric strength of the gas layer.

As a side effect of pulsing, the required electric power is reduced significantly.

4.3 DC ripple

In describing the physical processes in the electrostatic precipitator, a smooth high-voltage DC current is initially assumed. But a significant ripple is present during operation on the 50-Hz grid. It results from the interaction of the grid frequency, the filter capacity, and the corona effect.

This ripple increases since a phase approach is used to adjust the voltage, especially if the transformer is too large. But the descriptions above also show:

For dust with a high electrical resistance, a certain amount of ripple supports the goal of maximum precipitation.

It is possible to achieve control and discharge electrode discharge intervals in the 1 ms range, the half-wave duration is 10 ms, and the dust layer has a decay period extending over seconds. These factors fit together well and provide the tools for setting the maximum voltage and optimal current values for maximum dust precipitation.

From this perspective, there is no need to aim for ripple-free direct current. In addition, the millipulsing method described above can be modified and configured in a variety of ways with modern control methods. With old control systems, for example, the half-waves could either be turned on or off; in comparison, the half-waves can now be set to any desirable intermediate values (Fig. 7).

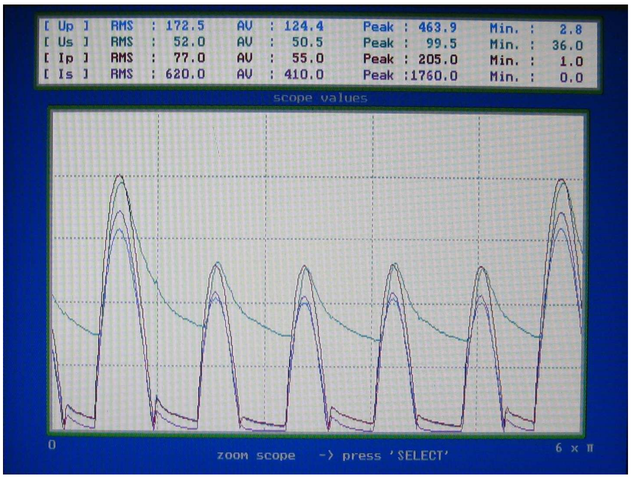

Fig. 7: Current and voltage progression during millipulsing: The time period shown is 60 ms; the slow decay of the secondary voltage after the pulse is clearly visible; the filter voltage is increased to a settable base voltage during the time in between pulses (fill-in). Source: Rico-Werk

Using the point of maximum precipitation - maximum voltage and optimal current - as a basis for consideration, the option of influencing the electrostatic precipitator's power requirements by varying the intermediate values presents itself. A coordinating CPU and a serial data bus (e.g. Profibus) are used to specify the target values for the voltage supplied by the high voltage regulators.

The actual output power is calculated by the high voltage regulators every ten milliseconds on the basis of the filter current and filter voltage measurements, and displayed on screen. The power target values are determined individually for every filter zone. They are the result of a higher-level control circuit, consisting of energy optimizing software and measurements of the current clean gas dust content (fig. 8).

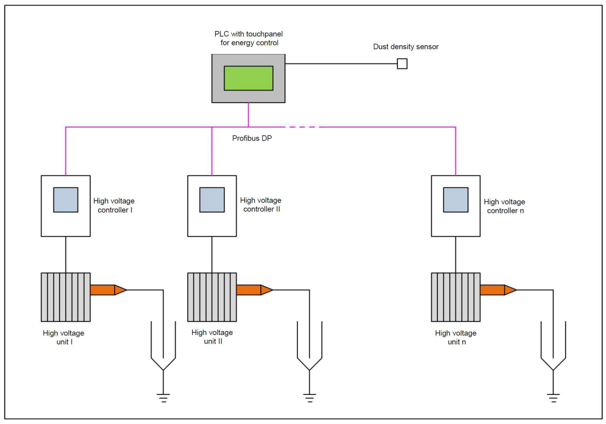

Fig. 8: Schematic control circuit for energy optimization

The energy optimization software operates with a programmable controller (PLC), which also controls rapping, runs the graphical interface, and transmits the power output target values to the high voltage regulators.

The power output target values are calculated on the basis of stored algorithms, parameter entries, and the current dust density value. This regulation process runs slowly when compared to the millisecond resolution of the high voltage regulators.

As a result, the amount of electrical energy required to maintain a specified clean gas dust value is minimized.

5 Maasvlakte power plant example

After 25 years of operation, the Maasvlakte power plant decided to replace the transformers and control systems for the electrostatic precipitators 1A and 1B as a preventative measure, in order to ensure reliable operation with good precipitation performance in the local sea air for another 15 years.

This opportunity was also used to increase the maximum voltage of the transformers at the same design current. No substantial changes were made to the filter itself. The electrodes, lane widths, and flow control structures were not modified. Therefore improvements to the operating characteristics are exclusively due to the modern electrical equipment of the filters.

The operating data of the housing 1A from 25/01/2010 (before the retrofit) and 05/07/2010 (after the retrofit) were compared. To obtain a meaningful comparison for the filter, the data for which the flue gas mass flow is 300 kg/s (approx. full boiler load) were extracted from the boiler load history. Since the flue gas temperature is 127 ℃ in all cases, the flue gas flow rates and speeds are also identical. The coal fired in the two cases is so similar that this is not expected to cause any significant differences in the precipitation behaviour.

Even if one only considers these load levels, natural dispersion still occurs because the load points were traversed from above or from below, slowly or quickly. But on average over the course of a day, these effects should largely cancel out. Measured with identical calibration, the following mean clean gas dust contents result:

- before the retrofit: 15.9 mg/Nm³ dry
- after the retrofit: 10.3 mg/Nm³ dry

The electric power draw of the individual high voltage units was also recorded. Before the retrofit, the control system tried to set a maximum voltage and current (fig. 9).

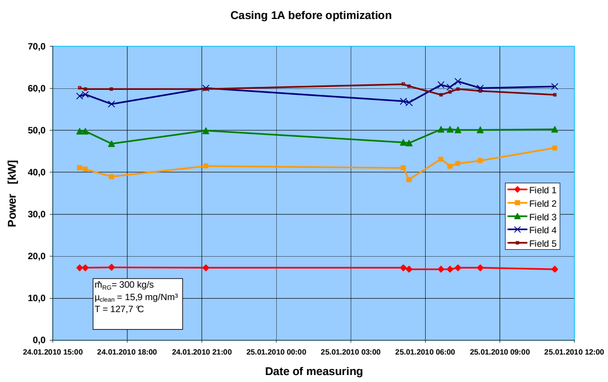

Fig. 9: Power draw of the filter before replacing the transformers and control system on 25/01/2010

After the retrofit, we used the coordinating CPU to specify a clean gas target value of 10 mg/Nm³ dry. It was possible to achieve this value with minimal power consumption (fig. 10)[1].

As fig. 9 shows, the power demand for direct regulation is up to 60 kW per high voltage unit. Due to the higher space charge, the power for the first field is ~ 18 kW and increases from field to field.

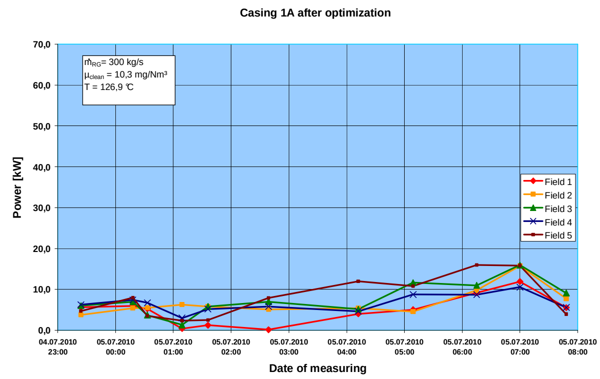

Fig. 10: Power draw of the filter after replacing the transformers and control system on 05/07/2010

The higher available voltage allows for a higher charge and – at the optimal setting – a clean gas content in the range of 7 mg/Nm³ dry. At a target value of 10 mg/Nm³ tr., all high voltage units rarely exceed a power draw of 10 kW per unit (fig. 10). This effect alone would already result in a power reduction of 80% in comparison to direct control before the retrofit.

This information also applies to housing 1B. However, one high voltage unit had failed before the filter was retrofit: further calculation would have been required in order to compare the before and after conditions. A direct comparison of the measurement results was not possible.

The indicated energy savings apply to full load operation. Under direct control, the electrostatic precipitator would allow for power consumption exceeding 60 kW per unit under partial load; the maximum would be reached when the flue gas flow rate approached zero: at the moment when there was no dust left to precipitate!

[1] Note: On 5/7/2010, operation was over a shorter period and for shorter full load periods. This results in a different time scale.

Therefore the savings in electrical energy are particularly noticeable when the boiler is under partial load.

Despite all the vague aspects still contained in the comparison, a significant reduction in energy consumption and the resulting reduction in CO2 emissions is undisputable.

Even if very low emission can be performed technically, it must always be considered: The lower the allowable clean gas contrations are set, the more important it is to weigh the health, ecological, and economic benefits – regardless of the technology used, because the building invest and power consumption required to achieve extreme target values both grow exponentially. Every increase in the electric power requirements also causes an increase in emissions of CO2 and other harmful gases, reduces the useful energy output of the power plant and results in increased consumption of resources.

Whatever the result of these discussions may be, the task facing manufacturers of electrostatic precipitators and the associated high voltage supply systems is to achieve the specified targets with the lowest possible electric power input.

6 Literature

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[2] Bühler, Stefan: Der Einfluß der Temperatur und der absoluten Feuchtigkeit auf das Durchschlagverhalten inhomogener Luftfunkenstrecken bei negativen Stoßspannungen.
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