Energy Optimization in Electrostatic Precipitators

Authors: Josef von Stackelberg, Holger Kleinwechter

Rico-Werk, Toenisvorst, Germany

1 Abstract

Electrostatic precipitators need electrical energy to separate the dust particles from the gas flow. The electrical energy causes the electrostatic field, which causes the Coulomb force inside the precipitator. The electrical current which flows through the electrostatic precipitator because of the electrical voltage over the ESP, is a secondary effect and can be helpful or disturbing for the precipitation rate.

Depending on the conditions inside the electrostatic precipitator, there is always an optimum of the amount of electrical energy with reference to an optimum of precipitation rate.

To optimize the precipitation rate of an electrostatic precipitator, there are certain technical measures to be implemented.

The article describes the technical background for the electrical conditions in the electrostatic precipitator and gives solutions for the arising problems.

2 Introduction

Electrostatic precipitators (ESP) are equipped with high voltage power supplies. Those are necessary as source for the high voltage which causes the electric field inside the ESP. The electric field force is the base for the Coulomb force which deviates the charged dust particles in the waste gas flow to be precipitated at the side walls.

According to the waste gas and mechanical precipitator conditions and with reference to the experiences of the design and construction engineer, the high voltage power supply has beside its maximum voltage a certain nominated power. When the conditions in the burning process change, the high voltage power supplies might no longer be sufficient for the process requirements; in this case modifications of the high voltage supply system are necessary or useful.

To understand why and how to modify the high voltage power supplies for the electrostatic precipitator, it is sensible and useful to consider the functional principle of the ESP.

3 The Functional Principle of an Electrostatic Precipitator

The dust containing waste gas is guided through a system of electrodes in an electric filter set-up. The electrodes are electrically counter-pole charged and therefore have electrical fields between them. An additional purpose of the electrodes is to contact the stream of exhaust gas for the flow of electricity between the electrodes. The electrode with a negative polarity is almost always the so-called discharge electrode; its geometry is such that the negative charge carriers (electrons) can emit from the surface with particular ease and move through the exhaust gas as free charges. The continuation of the description presumes that the discharge electrode has a negative potential. The positively charged electrode, which accordingly is used as the collecting electrode, has a surface topography to work as a collecting surface for the dust to be separated and to simultaneously low-ohm divert the negative charges transported by the dust particles via the large surface.

While the dust carrying exhaust gas streams through in between the electrodes, the dust particles are charged by different mechanisms.

- Charge by friction between the dust particles and the grounded exhaust gas pipes: Whenever two materials are rubbed against each other and at least one of them has insulating properties, the friction process results in the removal of charge media from one material and its adhesion to the other. During this process, the negatively charged electrons always migrate from the material with the more positive to the one with the more negative electron affinity (metals have primarily positive electron affinities).
- Ionization of the gas molecules by a powerful electrical field: If the molecules are in the state of an aggregate gas and are exposed to a powerful electrical field, these molecules may break down into ions, thus becoming charge carriers.
- Impact ionization: Other gas molecules are impact ionized by the highly accelerated electrons that have emitted from the discharge electrode and are moving through the electrical field, thus producing further charge carriers.
- Molecule ionization as a result of dissociation with dipole molecules (e.g. H_2O, SO_2, SO_3): The dipole molecules adhere to the molecules to be ionized, causing a relocation of the electrons and ultimately cancel out the forces between the atoms in the molecule and the groups of atoms are separated.
- Charging of particles by free electrons and attaching ions: while the dust particles move through the space charge cloud, free electrons and ions attach to them and create a charge attached system.

The charged or charge carrier attached dust particles are impacted by the force of the electrical field. This electrical force - the Coulomb force – diverts the stream direction of the charged particles into the direction of the electrical field lines until they reach the counter pole charged electrode: the negatively charged particles move to the collecting electrode, while the positively charged particles attach themselves to the discharge electrode (Figure 1).

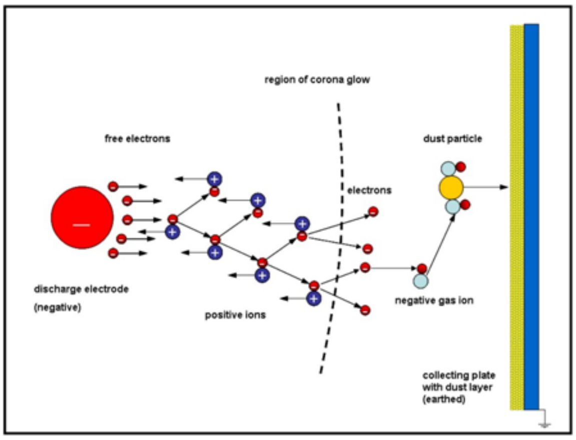

Figure 1: Efficacy principle of the electrostatic precipitator with negatively charged discharge and grounded collecting electrode; the dust particles are negatively charged and subsequently migrate to the collecting electrode [1]

The collecting electrode is grounded and simultaneously connected with the positive potential of the voltage source. As a result, the negative charged electrons on the dust particles, once they have attached to the collecting electrode, flow out through the former. Given that a residual negative voltage is always present on the surface of the dust layer on the collecting electrode, the dust particles are held back by the collecting electrode. Over time, they form a dust layer that is more or less firm and is removed in certain intervals with rapping hammers. The dust layer is loosened and falls into the catching and collection devices.

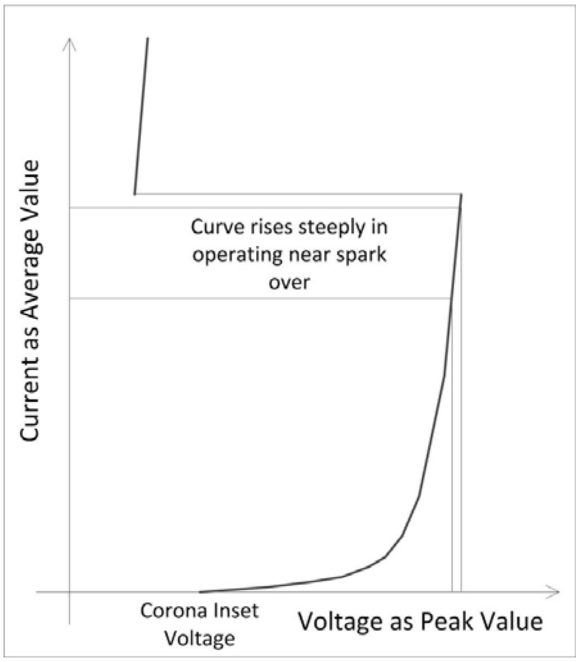

Figure 2: V-I-index line for an electric filter; the corona inset voltage is clearly identifiable as the minimum voltage for reasonable flow of electrical current [2]

Specifically, there are a number of parameters that have a significant impact on the behavior of the electrostatic precipitator:

- The corona inset voltage is the minimum voltage that must be present between the electrodes to ensure that a reasonable number of electrons leaves the discharge electrode and enters the space (Figure 2). The corona inset voltage depends mainly on the shape of the electrodes (slender, tipped, edgy electrode shapes reduce the corona inset voltage because the electrical field strength increases on the tips and edges); on the clearance between discharge and collecting electrodes and therefore on the electrical field strength between the electrodes; on the temperature of the discharge electrodes as well as the electrode material.

- The distance between discharge and collecting electrodes determines the electrical field strength for a defined voltage. Further on the distance describes the route length that has to be covered by a dust particle at a maximum before it arrives at the collecting electrode. Besides the distance between the electrodes and the shape of the discharge electrodes determine the electric filter index line when the filter is in idle mode.
- The specific dust resistance of the dust particles in the filter determines how much current will flow through the electric filter once voltage is applied. The conductivity of the dust is the reciprocal value of the resistance.

  When considering the conductivity of the electric filter, there has to be distinguished between the range which the floating individual dust particles move through the gas and the area where dust particles are adhering more or less firmly on top of each other to the collecting electrode, given that the conductivity of the electric filter is reduced as the dust layer thickness on the collecting electrode increases and the dust conductivity becomes lower. As a rule, only the specific resistance of the adhering dust, which has an impact on the conductivity of the filter through the dust layer thickness on the collecting electrode, is assessed. In practical applications, specific dust resistances occur in the range of 10^{7} ... 10^{12} $\Omega \cdot$cm; in some cases, e.g. in sinter plants, specific dust resistances can increase to up to 10^{14} $\Omega \cdot$cm [2].
- The composition of the gas in the filter also determines how much current will flow through the electrostatic filter if voltage is applied. In the gas flow range, the conductivity is contingent upon the so-called electron affinity of the gas molecules. Even small modifications of the composition of the gas can result in substantial conductivity changes.

  A specific resistance of about 10^{11} $\Omega \cdot$cm may be presumed for air (about 80% N_2 and 20% O_2).

Depending on its concentration, sulphuric oxide increases the fluid resistance to up to 1250%. In turn, the reduction of oxygen in the air reduces the resistance depending on the degree of reduction by up to 40%. Overall, the specific electric resistance of gas in an electrostatic precipitator can be presumed to be in the range of $8 \times 10^5 \ldots 2.5 \times 10^7$ $\Omega\cdot$cm (Figure 3).

- The dielectric strength of the filter is a highly dynamic parameter, which changes constantly. The dielectric strength voltage determines the maximum electrical field strength that can be generated between the two electrodes. In turn, the dielectric strength is contingent upon the distance between and the type of electrodes, the types of dust streaming through, the composition and temperature of the exhaust gas, the dust deposits on the electrodes, etc. The dielectric strength may drop all the way down to the corona inset voltage. In the event of a spark over, the voltage inside the filter may even drop far below the corona inset voltage if an arc is generated and comes to a standstill. In this case, the electrostatic precipitator is no longer subject to the conditions for the flow of current in gases. Instead, a very low ohm plasma channel establishes a short circuit between the electrodes.

  As far as the dielectric strength is concerned, one must also distinguish between the dielectric strength of the dust layer and that of the exhaust gas zone between the electrodes. Ultimately, an electric spark going through the dust layer can initiate a spark over in the exhaust gas space.

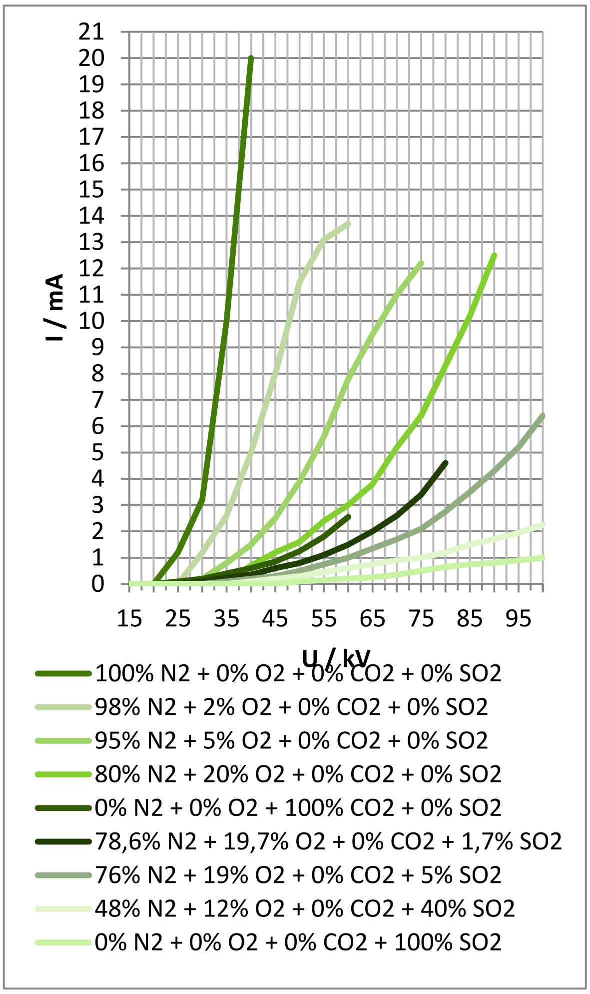

Figure 3: Voltage-current patterns of different compositions of gas; even small amounts of an added gas can have a massive impact on the overall patterns [2; chapter 4.2, figures 4.5 and 4.6].

- The electrical capacity of the electric filter depends on the effective surface of the electrodes located opposite each other and the type of dusts introduced. The latter determines the amount of charge carriers that can be stored in the electric filter and that flows through the short circuit path in the event of an electric spark over before the short circuit channel can be closed again [3].
- Finally, there are various sources of voltage with different operating modes that are used to assist with the generation of high voltage for the electrical field in an electric filter.

4 Operating Modes of High Voltage Generators

Apart from the high voltage cascades, the use of which still plays only a minor role in electric filters because of their practically low output limit, high voltage generators primarily consist of an electromagnetic voltage converter which is in the case of grid frequency a transformer, in all other cases a transmitter, and a rectifier set in order to turn the transformed AC voltage into DC voltage. Various systems are available to control the high voltage or flowing current or to provide special types of current on a case by case basis.

In the most cases, AC voltage is fed into a transformer through the ignition angle controlled thyristor set (Figure 4). On its secondary end, the transformer delivers high AC voltage, which is converted into a more or less pulsating DC voltage through a rectifier (Figure 5). A compatibly equipped controller makes it possible to bring a wavy DC voltage, which can be adjusted or is pulsating with overlapping voltage pulses, into the filter with the assistance of this transformer-rectifier combination (Figure 6).

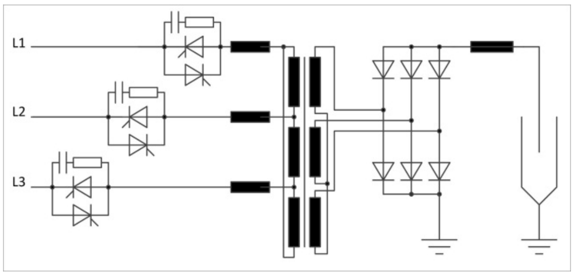

Figure 4: Principle of a three phase high voltage power supply system with thyristor setting, high voltage transformer and bridge rectifier; the output voltage connection includes a choke to protect the power supply from high frequency disturbances

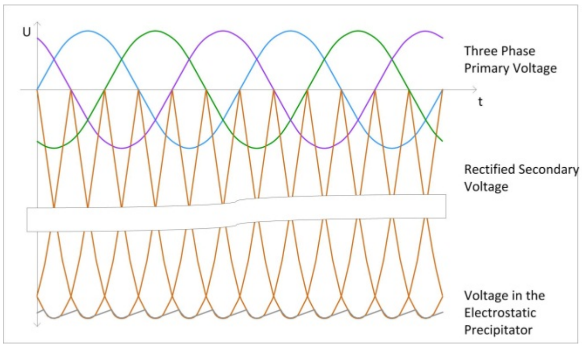

Figure 5: Electric filter voltage (gray) of a three phase high voltage rectifier device if the sinus waves are at their maximum setting; the residual waviness of the electric filter voltage is highly dependent upon the filter capacity and dust resistance

The time intervals between those voltage pulsations depend primarily on the grid frequency.

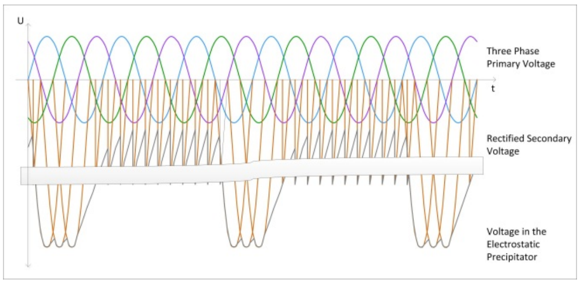

Figure 6: Pulse operation with a three phase device; between pulses, when the half wave is at the maximum control level, the angled half waves are used to "fill up" the voltage in the filter to the level that depends on the respective filter conditions

5 High Ohmic Dust Situations

The conditions for an electrostatic precipitator to divert dust particles in a satisfying manner from the waste gas are a strong electric field in the waste gas flow area, particles which can be charged properly and enough space inside the electric field in flow direction that the particles can move to the wall electrodes rsp. an adjusted flow velocity of the waste gas.
There are several scenarios which complicate the precipitation mechanism.
One of them is very high dust resistivity, i.e., the dust layer at the wall electrode gets more electrons from the arriving particles on its surface than the layer resistance allows to flow off. In this case, a high voltage is generated over the dust layer (figure 7).

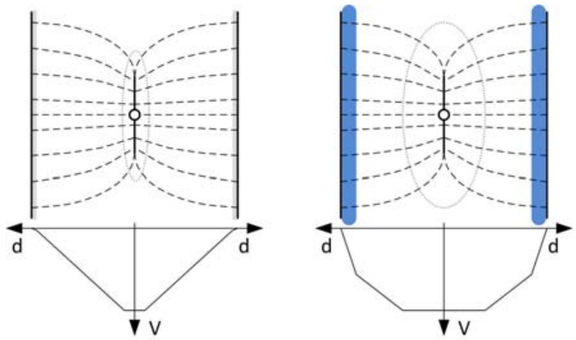

Figure 7: Schematic potential development in an electric filter with two collecting electrodes and a centrally positioned discharge electrode. Indicated on the left is a thin low ohm layer of dust (gray); on the right a thick, high ohm layer of dust (blue). In the middle zone around the discharge electrode is the room charge cloud, the size of which ultimately also depends on the capability of the charge media to flow out through the collecting electrode. The bottom of the drawing depicts the potential progression through the location between the discharge and the collecting electrode: the thick high ohm layer of dust results in a very high voltage level with an extreme spark over risk caused by initial ignitions in the layer of dust

The high voltage loss over the dust layers leads to two effects: The voltage over the gas flow area becomes significantly lower which leads to decrease of the electric field strength within this area. Finally the Coulomb force weakens, the precipitation rate is no longer sufficient.
Secondly the voltage over the dust layer becomes so high, that there occur spark overs within the dust layer. They form a plasma channel which throws ions into the gas flow channel, the so-called back corona effect starts. Further this heavy ionization may lead to a growing of the plasma channel through the gas flow area, the whole area

between the corona and the wall electrode is short circuited, the electric field force vanishes completely.

The solution for this problem is to charge the gas flow area with a short timed high voltage pulse and then give the dust layer time to discharge. This is practiced with so called pulsating voltages (see also figure 6).

During pulse operation, not every half wave of the DC supply is ignited fully, but only a fraction of the waves – e.g. every third, fifth, seventh, etc. Depending on the controller system, the half waves between the fully ignited half waves are either partially charged to obtain a so-called fill-in voltage or are completely deactivated to make things simple.

A fully ignited half wave is used to charge the capacitor of the electric filter until it reaches the high voltage level; during breaks, the voltage drops exponentially based on a time constant determined by the dust resistance on the collecting electrode and the capacity of the electric filter.

Using this pulse voltage instead of continuous voltage creates a possibility to reduce the energy consumption of the electrostatic precipitator.

Indeed, if the situation inside the ESP is a high ohmic one it is possible to reduce the energy consumption significantly and even increase the precipitation efficiency.

6 Energy Optimization Systems

The energy optimization solution for high voltage generator systems is a supervisory control system that manages the energy supplied to high voltage generators to ensure that only the electrical power required is entered into the filter zone to attain the desired residual dust content in the exhaust gas chimney. Depending on the concentration of dust, the individual high voltage controllers are constantly actuated and thus ensure that the conditions in the electric filter are optimal (Figure 8).

The amount of energy which can be reduced in relation to full power mode, depends on some issues, e.g. the sort and quality of the fuel which is the base for the dust composition, the generator power (is the generator in full or in part power modus), the position of the dust density sensor (the farther the sensor is away from the filter the more dead times have to be considered in the regulation algorithm), the ability to adjust the controller system to the ESP conditions and the rapping and rapping break times (during rapping it is not always recommended to run the ESP zones with pulse modus).

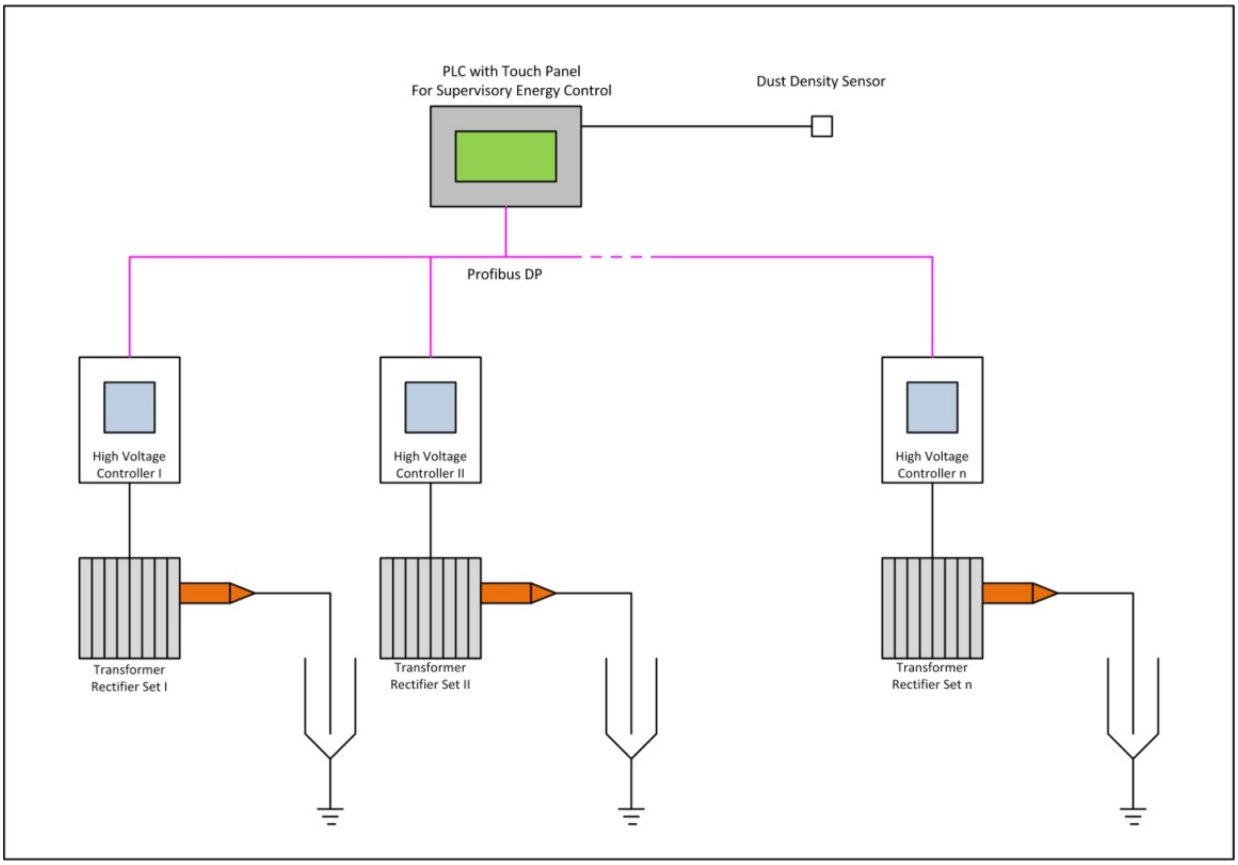

Figure 8: Energy optimization control principle with supervisory high voltage power system control depending on the density of the dust on the electric filter output

A calculation example may indicate the potential to save energy and money: The reduction of the electrical power for the high voltage generation by 500kW leads to the reduction of the annual energy demand of 2.190.000 kWh/a at a twelve hour daily runtime of the generator (this runtime may occur because of wind turbines and photo voltaic systems which are connected to the grid).

The reduction of energy efforts reduces directly the cost efforts by 153.000 €/a at 7ct/kWh. Further on the reduction of energy effort reduces the carbone dioxide emission by 1686 to/a.

Finally the reduction of power inset in the electrostatic precipitator leads to an increased power plant efficiency rate which depends on the generator power but is measurable.

7 Low Ohmic and Heavy Load Dust Situations

With low ohmic filter conditions and heavy dust load situations the requirements to the high voltage power supply is vice versa. The power supply has to deliver the voltage over the whole time; even the pulsating voltage of a single phase unit with its bridge rectifier

means a significant reduction of the electric field force over the time and therefore a reduction of precipitation rate.
In different applications like a wood fired power plant, a lignite power plant or a waste incineration plant, the simple replacement of single phase units by three phase systems increases the precipitation rate significantly, that the dust density is brought down e.g. from 100 mg/Nm³ to 10 ... 20 mg/Nm³. Thus the power plant is able to go below the emission rate limits rsp. can increase the generator power.

8 References

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