Enhanced Electrical Model for the Electrostatic Precipitators

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1 Summary / Abstract:

Electrostatic precipitators are used to separate dust loads from the exhaust gases by using electrostatic fields. The electrostatic precipitator has the advantage, compared with the fabric filter, that there does not exist any systematic lower limitation for the dust particle size [1].

For efficient usage of the electrostatic precipitator it is necessary to understand the rather complex electrical model for the precipitators. This model is based on the electrical characteristics of the dust particles and the precipitator construction and exceeds the filter modeling which is described in the electrostatic precipitator's standards. Besides the resistance values of the dust it also considers the permittivity of the particles and molecules and adds a capacitor. Further on the flashover event is included in the model. Thus the model considers also the dynamic behavior of the precipitator besides the static resistances.

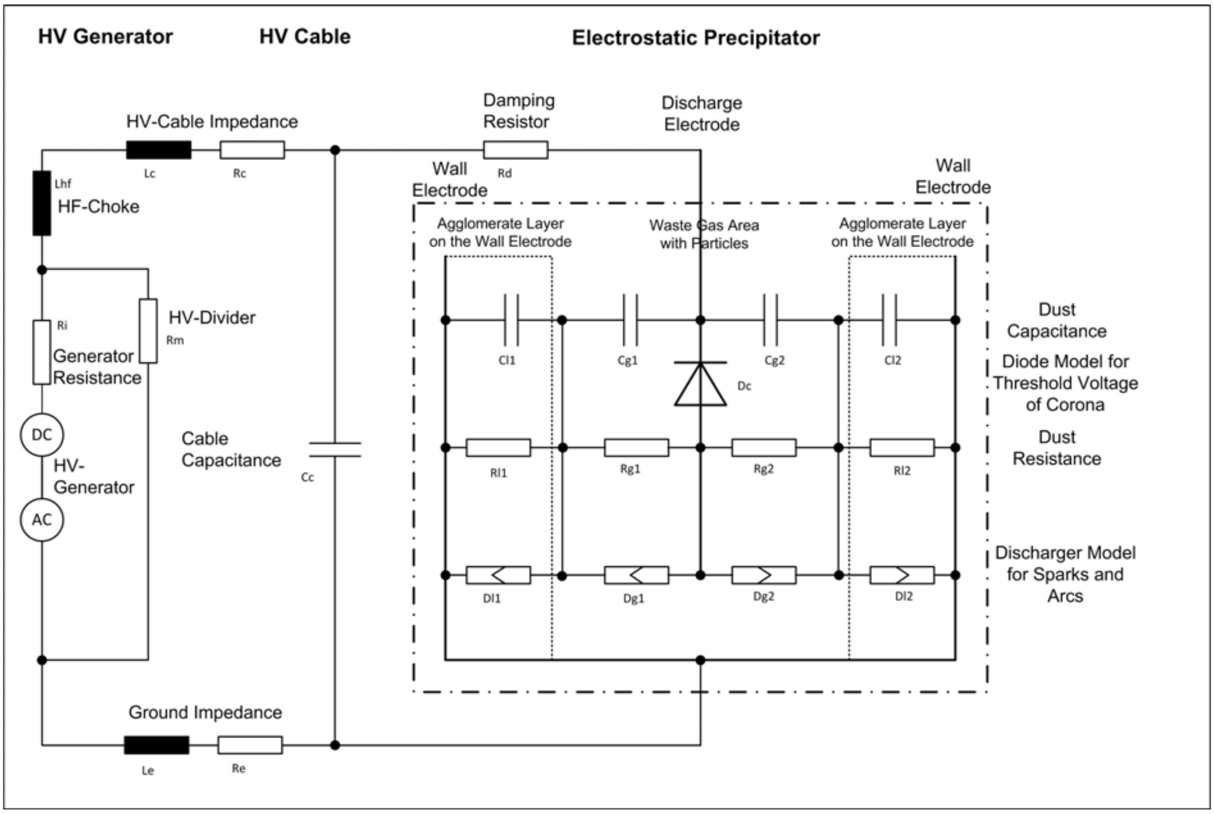

Fig. 3-1: Enhanced Electrical Model for the Electrostatic Precipitator

2 Introduction

Electrostatic precipitators separate dust loads from exhaust gases by using electrostatic field force. As there is no systematic lower limitation for the size of the dust particles, the electrostatic precipitator has an advantage against the fabric filter. But to use simply the electrostatic force seems not in every case the optimum solution to get clean gas, e.g. for the

so called difficult dusts. In those cases it is not always easily possible to get as much electrical field force as it is necessary to keep the dust rate below the limit rate. To make the situation even worse, the electrical conditions within the precipitator are in a steady move, therefore the optimization has to be adjusted permanently.
It is necessary to consider the rather complex electrical correlations within the precipitator, in combination with the model of the high voltage generator and the current path within the cable to find an optimized electrical field for every situation which may occur within the precipitator. From the enhanced model it is possible to derive automatic online detection systems which enable a controller system to optimize the high voltage power supply for the electrostatic precipitator.

3 The Enhanced Electrical Model

The enhanced electrical model includes the power supply, the high voltage connection cable and the precipitator itself (Figure 3-1). Sometimes, the one or other component has not to be considered, e.g. when the transformer rectifier set of the power supply is placed close to the discharge electrodes, the capacitance and the inductance of the cable can be neglected. Further on in this case most time there isn't installed any damping resistor.

3.1 The Components

The HV generator model itself consists of a DC part and an AC part, because of the rectified AC voltage. The AC and the DC part, which can be indicated at the discharging electrode of the precipitator, depend on the load conditions, i. e. of the values of the resistance, the capacitance and the inductance. Further on the generator includes the generator resistance, mostly dependent of the rectifier and therefore depending on the load current, and depending on the transformer construction, which limits the short circuit current to 2,5 ... 3,5 times of the nominal current.
The HV cable includes mainly two energy buffers, the cable capacitance and the inductance. Those values are mostly fix, but they are working like a low pass filter, and in case of a flashover short circuit it has to be considered that those energy buffers are also to be discharged by the flashover.
The model of the precipitator as drawn in the figure 3-1 is still a simplification. The detailed model consists of infinitesimal small parts of diodes, resistors, capacitors and dischargers in the waste gas area and in the agglomerate layers (Figure 3-2).

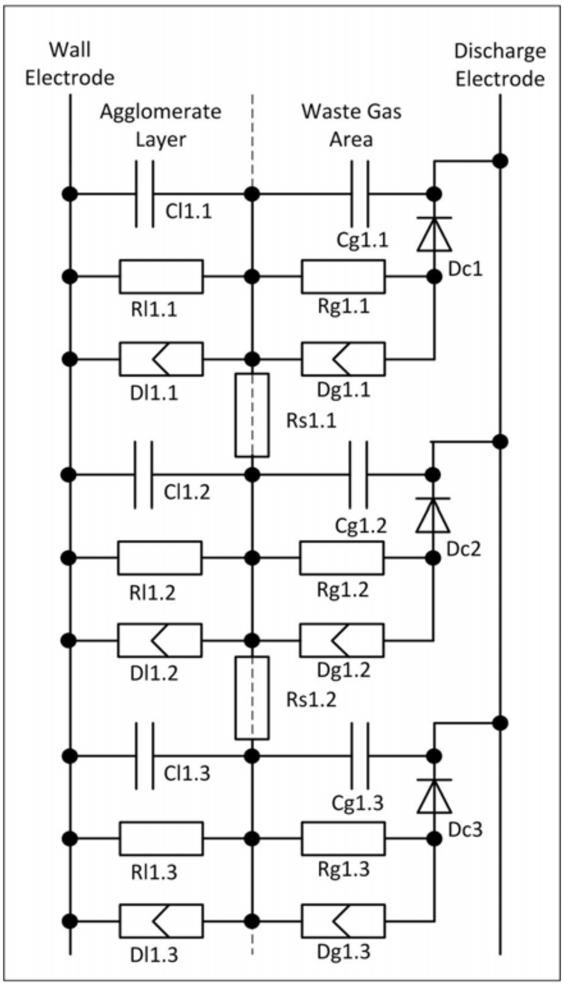

Fig. 3-2: Infinitesimal small segments as electrical model network within the precipitator

The most important difference between figure 3-1 and figure 3-2 is the surface resistor Rs, which conducts the charges between the infinitesimally small segments when there are different resistors rsp. capacitors within the segments.
The diode Dcx represents the behaviour of the discharge electrode with reference to the knee voltage, where charges begin to emit from the discharge electrodes, and to the non-linear relation between current and voltage [2] (Figure 3-3).
The resistors Rgx represent the resistance of the waste gas area, loaded with particles, for the electrical current, while the resistors Rlx stand for the agglomerate layer resistance, based on the resistance of the dust particles. There is a distinction between the resistances of the gas area and the agglomerate layer, because in the gas area the dust particles are mostly carrier for the electron charges or may be a disturbance in the electron movement, while in the agglomerate layer on the wall electrodes the dust particles are some kind of physical resistor and conductor of electron charges. Both those resistances have been

analyzed by many experiments [3, 4] and have been topic of many presentations and discussions.

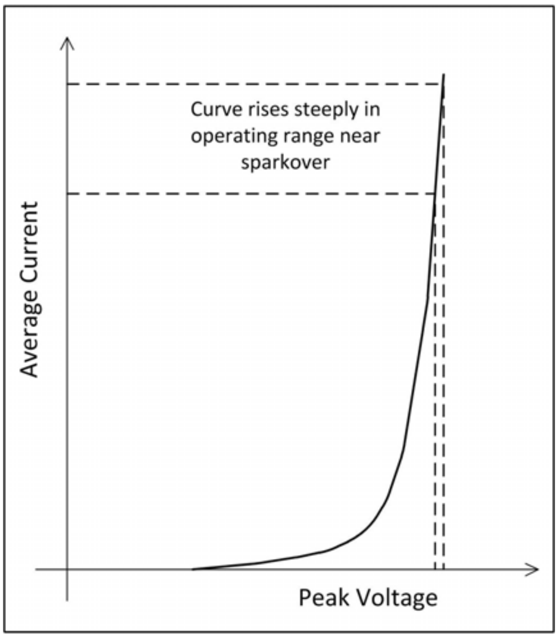

Fig. 3-3: The voltage-current-graph of the electrostatic precipitator is similar to the characteristic of a diode graph

The capacitors Cgx represent the capacity between the discharge electrode and the surface of the agglomerate layer. Those capacitors are both an energy store and a dynamic component within the electrical network. Similar functions have the capacitors Clx within the agglomerate layer.
The consideration of those capacitors will be the main topic of the next chapter of the theoretical background.
The discharger models Dgx and Dlx represent the arcs, the sparks and the flashover behaviour. Like the resistor and the capacitor models, the dischargers are different in the gas area and in the agglomerate layer. Their theoretical model will be also considered closely in the next chapter.

3.2 The Theoretical Background

The Diode Model

The emission of electrical charges from a material because of the force of an electrical field is described by the so-called Fowler-Nordheim equation [5]:

$$J = \frac{q^3 \cdot m_{eff}}{8 \cdot \pi \cdot m_{diel} \cdot h \cdot q \cdot \Phi_1} \cdot E_{diel}^2 \cdot e^{\frac{-8 \cdot \pi \cdot \sqrt{2 \cdot m_{diel} \cdot (q \cdot \Phi_1)^3}}{3 \cdot h \cdot q \cdot E_{diel}}} \qquad (3\text{-}1)$$

with
J = Current density
q = Charge of the electron (-1,602 · 10^{-19} As)
m_{eff} = Effective mass of electron within the electrode (depends on the electrode material)
m_{diel} = Effective mass of electron within the dielectric (depends on the dielectric material)
h = Planck's constant (6,626 · 10^{-34} Js)
$q \cdot \Phi_1$ = Barrier energy (depends on the electrode material)
E_{diel} = Electrical field force in the dielectric

The Fowler-Nordheim equation leads to an E-j-relation which is comparable with the U-I-relation according to the literature and numberless tests (figures 3-3, 3-4).

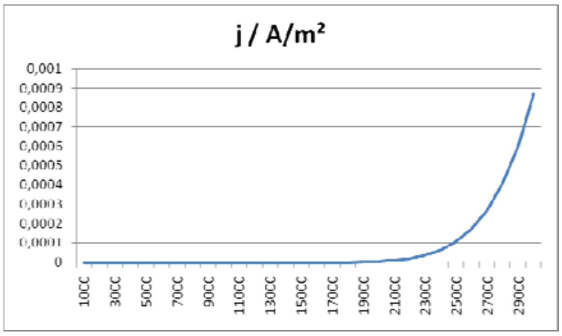

Fig. 3-4: Model graph of the Fowler-Nordheim equation (abscissa = electrical field force in V/m; ordinate = current density in A/m²) with following assumptions: $q \cdot \Phi_1$ = 4,8 · 10^{-19}As, $\frac{q^3 \cdot m_{eff}}{8 \cdot \pi \cdot m_{diel} \cdot h}$ = 1 · 10^{-28}, $\frac{-8 \cdot \pi \cdot \sqrt{2 \cdot m_{diel}}}{3 \cdot h \cdot q}$ = -4 · 10^{33}

As the diode model mostly covers the beginning of the corona behavior according to the Fowler-Nordheim relation, the model can be used for the enhanced electrical model for the electrostatic precipitator.
The characteristic values of the diode model depend on the materials the discharge electrodes consist of and of which shape they are; i.e. when a dust layer is on the electrodes or when the electrode peaks are erased the behavior may change.

The Resistor Model

The resistors Rgx and Rlx are of different kinds.
In the waste gas area the conduction of the current is a flow of electrons and negative charged ions from the discharge electrode and from the waste gas to the wall electrode and a (smaller) flow of positive charged ions from the waste gas to the discharge electrodes [6].
The resistance depends on a bundle of parameters, e.g. the temperature, the dust materials, the dust flow velocity etc.

In the agglomerate layer the dust particles mostly have physical contact to each other, the current conduction happens by movement of electrons from particle to particle and by pseudo-movement of "holes", similar to the conduction in a semiconductor. In the agglomerate layer the resistance value also depends on different parameters like temperature or force which presses the particle to the next one.

The measurement of the dust resistance has already been the source for many research and investigation and shall not be the main topic of this considerations.

The Capacitor Model

The electrostatic precipitator is in principle a huge capacitor: There are two conductors mounted face to face to each other and between the conductors is a more or less insulating layer rsp. there are two layers, as there is the waste gas area with dust particles and there is the agglomerate layer (figure 3-5).

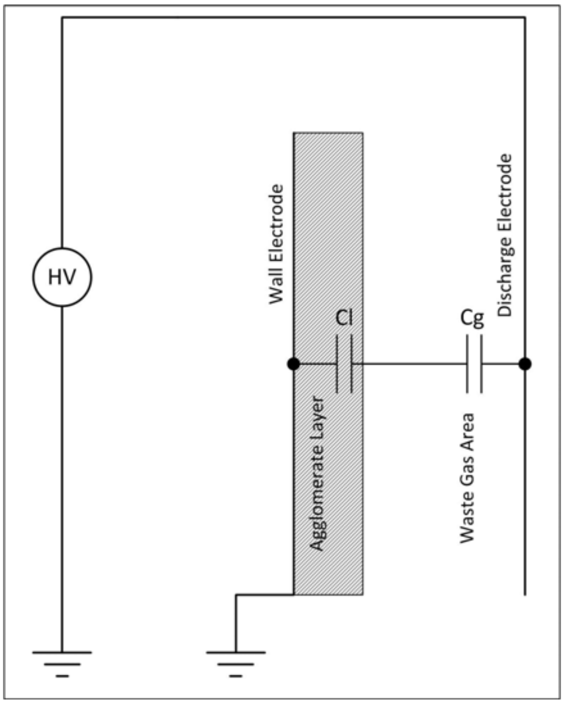

Fig. 3-5: Capacitor models in the electrostatic precipitator; the capacitors in the waste gas area have to be distinguished to the capacitors in the agglomerate layer

A plate capacitor is calculated with the formula

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d} \quad (3\text{-}2)$$

with

ε_0 = Permittivity constant (= $8{,}854 \cdot 10^{-12}$ As/Vm)

ε_r = Permittivity number, depends on the material between the capacitor plates

A = Plate size

d = Plate distance

To use this formula for consideration of the precipitator capacitors, it is approximated that the discharge electrode is also a plate and the distance between the electrodes is a constant.

The plate distance for the agglomerate layer capacitor Cl is the thickness of the agglomerate layer, which changes permanently, because during the precipitator process the thickness increases, and with a rapping it is decreased abruptly. The distance for waste gas area capacitor Cg is the distance between the electrodes, reduced by the thickness of the agglomerate layer. As the thickness of the agglomerate layer may be a small fraction of the whole distance, in the waste gas area distance the changes are not significant.

The other distinction criteria between the waste gas capacitor Cg and the agglomerate layer capacitor Cl is the permittivity number (Table 3-1).

Chemical Symbol	Name	Permittivity Number
SiO2	Silicon Dioxide	6 … 8
Al2O3	Dialuminum Trioxide	9
Fe2O3	Ferric Oxide	
TiO2	Titanium Oxide	>100
CaO	Calcium Oxide	
MgO	Magnesium Oxide	
Na2O	Sodium Oxide	
K2O	Potassium Oxide	
SO2	Sulphur Dioxide	
P2O5	Diphosphor Pentoxide	
H2O	Water	80,4 (liquid)
CO	Carbon Monoxide	
CO2	Carbon Oxide	

Tab. 3-1: Consistency of waste gas and ash [7, 8, 9]

The impact of the permittivity number ε_r on the precipitator behavior is significant:

There is a certain electrical field force between the precipitator electrodes:

$$E = \frac{U}{d} \left[\frac{V}{m}\right] \quad (3\text{-}3)$$

with

E = Electrical field force

U = Electrical voltage
d = distance between the electrodes
The electrical field force leads to an electrical displacement density:

$$D = \varepsilon_0 \cdot \varepsilon_r \cdot E \quad \left[\frac{As}{m^2}\right] \qquad (3\text{-}4)$$

with
D = Electrical displacement density
ε_0 = Permittivity constant (= $8{,}854 \cdot 10^{-12}$ As/Vm)
ε_r = Permittivity number, depends on the material between the capacitor plates
E = Electrical field force

The electrical displacement density describes the amount of (negative) charges (= electrons) per square meter placed on the discharge electrode:

$$D = \frac{Q}{A} \qquad (3\text{-}5)$$

with
D = Electrical displacement density
Q = Electrical charge
A = Plate size

This relation leads to a certain field force when a certain material is placed between the discharge and the wall electrode:

$$\frac{Q \cdot d}{\varepsilon_0 \cdot \varepsilon_r \cdot A} = U \qquad (3\text{-}6)$$

with
Q = Electrical charge on the electrodes
d = Distance between the electrodes
ε_0 = Permittivity constant (= $8{,}854 \cdot 10^{-12}$ As/Vm)
ε_r = Permittivity number
A = Electrode plate size

Or to consider it from the other side: If a certain amount of electrons per square meter are placed on the discharge electrode, a certain voltage will be measurable between the electrodes. The voltage depends on the material between the plates.

Like for the resistors, the capacitor models of the waste gas area and the agglomerate layer have to be distinguished, as in the gas area the dust particles are a very small part of the whole dielectric medium while in the agglomerate layer it is mostly the mix of molecules as listed in table 3-1. Further on, in the agglomerate layer the capacitor is changing its value because of the growing of the layer thickness by the time and abrupt decreasing during the rapping process; but the growing is slow over the time. In the waste gas area the changes of material are comparable fast when a small cloud of different dust particles floats through the precipitator and changes the dielectric medium consistency.
Some behavior situations are discussed in 3.3.

The Discharger Model
The electrical model for a discharger is comparable with a thyristor (Figure 3-6). The discharger behaves similar to a thyristor which gets no gate current. There is a very small blocking current within the forward blocking region while the voltage over the discharger is increased. At a certain voltage, the forward-breakdown voltage, an avalanche of charges breaks through the high ohmic area and causes lots of ionized molecules which start to conduct the current, a plasma channel is initialized. This plasma channel is very low-ohmic, its V-I-behavior is linear like that one of a resistor ("on state" on the diagram). The voltage breaks down. The plasma channel needs a certain minimum current to remain conducting, the so called hold current. When this limit current mark is undershot by the flowing current, the plasma channel disappears after it is cleared from the charges.

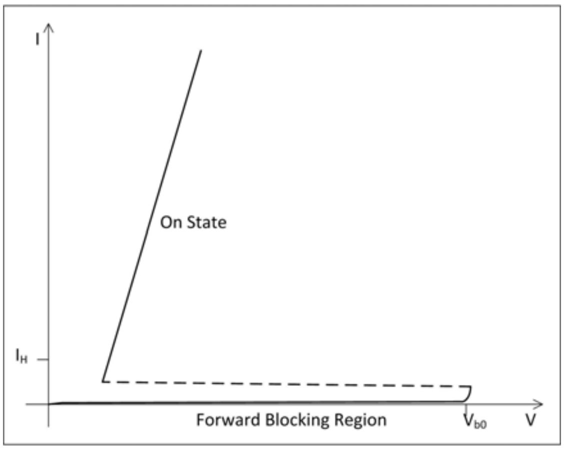

Fig. 3-6: V-I-Diagram of a Thyristor with V_{b0} is the Forward-Breakdown Voltage and I_H is the minimum Hold Current [10]

The discharger can be detected as well in the gas area as in the agglomerate layer. The breakdown voltages and the ignition time of both dischargers depend on the materials of which the waste gas area and the agglomerate layer consist each. Further on the breakdown voltage depends on the temperature and other parameters [11].

3.3 Examples for Behavior

As the electrical components within the electrical precipitator are described, it is possible to consider some scenarios of behavior.
The goal to drive the electrostatic voltage within the precipitator is always to come as

close as possible to the breakthrough point of the precipitator (= the breakdown voltage of the discharger models), but with as few breakthroughs (= sparks and flashovers) as possible, as a breakthrough means always a breakdown of precipitator voltage and therefore a bad precipitation rate, mostly in combination with high precipitator energy turnover.

Scenario 1: Voltage Divider between the Precipitator Plates

The first scenario considers rather stable material conditions without high time gradients. There is a certain capacitance in the waste gas area and a certain capacitance in the agglomerate layer. In parallel to each capacitance there exist both a resistance and a discharger (Figure 3-7).

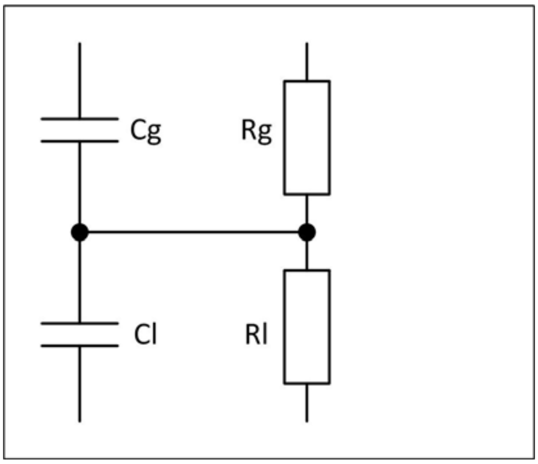

Fig. 3-7: R-C network for the stable condition within the Electrostatic Precipitator; the discharger is no relevant component for the dynamic behavior of the circuit and is therefore not drawn

The values of the resistors and the capacitors are changing permanently, as the dust layer grows while the dust is precipitated, and is abruptly reduced by the rapping process (Figure 3-8).

The component values in the gas area are rather constant, as the only time dependent factor, the thickness of the gas area, does not change its value significantly. The reason is, that the distance from the discharge electrode to the surface of the dust layer is mostly the same (see also equation 3-2), and the distance is one of the determining factors for the resistor and for the capacitor.

For a quantitative evaluation of this context, there shall be made a calculation with some numbers for a capacitance construction with air as dielectric:

$$C = \frac{8{,}85 \cdot 10^{-12}\,\frac{As}{Vm} \cdot 240\,m^2}{0{,}2\,m} = 11nF \quad (3\text{-}7)$$

The similar capacitance can be reached with a dielectric with $\varepsilon_r = 10$:

$$C = \frac{8{,}85 \cdot 10^{-12}\,\frac{As}{Vm} \cdot 10 \cdot 240\,m^2}{0{,}02\,m} = 11nF \quad (3\text{-}8)$$

which matches a dust layer of 20mm on the wall electrode.

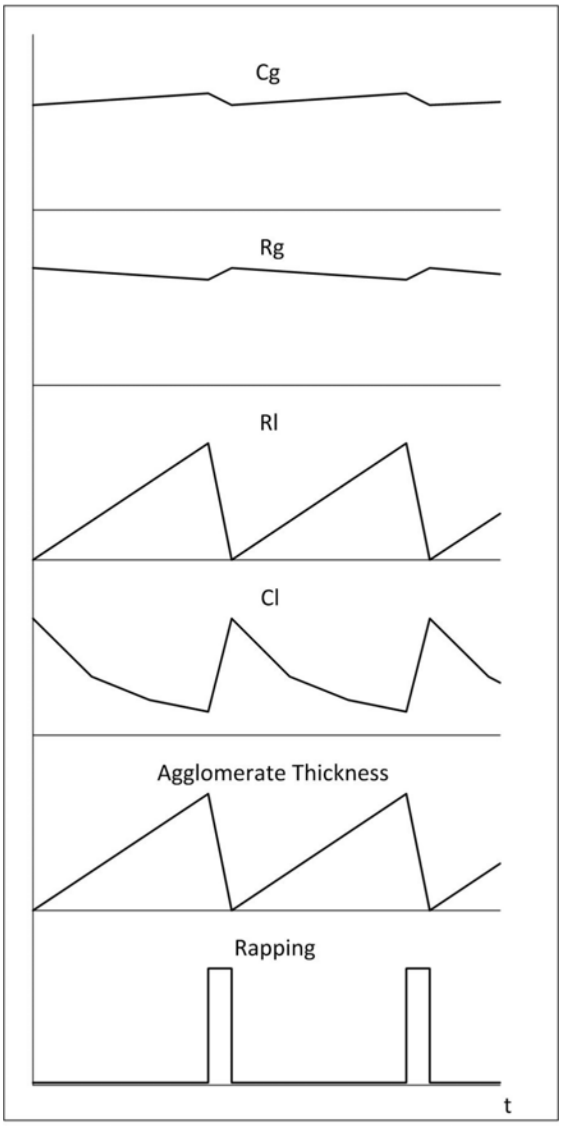

Fig. 3-8: Qualitative diagram for the time dependency for the values of resistors and capacitors; the agglomerate layer thickness and the rapping cycles are the determining parameters for the resistors and capacitors

As the gas area is reduced by 10% to make up this serial capacitor, the gas area capacitor is reduced by 10%. The total capacitance can be calculated to C_{total} = 5nF.

As soon as a rapping process starts, the dust layer (capacitor) disappears and the total capacitor will be 11nF again.
For the charge carrier situation over the whole plate system, this changes mean that the slow reduction of the capacitance – which means a slow increasing of the voltage or requires a slow discharging over the resistance – can be met by an intelligent controller easily, and the fast increasing of the capacitance during the rapping would lead to a decreasing of the voltage which will be compensated by the high voltage supply.

Scenario 2: Change of Material consistency between the Precipitator Plates
As long, as the conditions are stable, nothing happens:
- The discharge electrode carries a certain amount of electrons in and on it.
- It transports a constant flow of charges into the waste gas area.
- The waste gas area has a certain consistency with resistance and capacitance and electrical voltage (= electrical field force).
- The electron current flows to the wall electrode, through the earthing connection and back to the generator.

When in the material consistency there is a rapid change and the permittivity becomes lower with rather high velocity, e.g. caused by a cloud of dust with low permittivity, according (3-6) the electrical voltage increases multiplied by the same factor as the permittivity decreases (Figure 3-9).

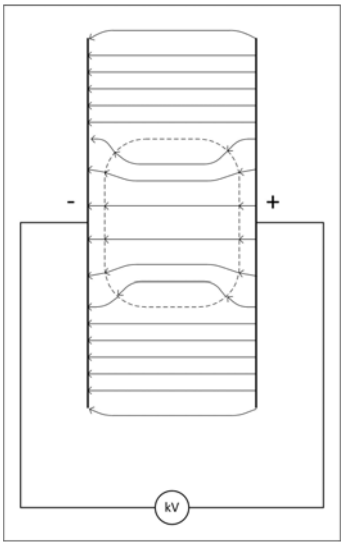

Fig. 3-9: Cloud of dust within the plates of the capacitor

A quantitative estimation of the change of behavior could be based on a dust density of 0,015 kg/m³. The materials of the dust have a permittivity number ε_r of about 10, some compounds got 100 (see Table 3-1). For the estimation the permittivity for the dust is assumed with ε_r = 10. The gas temperature shall be 400K; the average density of the dust particles is 3 kg/dm³.
The carrier gas should be mostly carbon dioxide with a density of 1,365 g/m³ at 400K and an $\varepsilon_r \approx 1$.

For capacitance calculations the volumes of the materials have to be considered [12]. The total dielectric is the volumetric average value of the gas and the dust particles:

$$V_{dust} = \frac{0{,}015 kg \cdot dm^3}{3 kg \cdot m^3} = 5 \frac{cm^3}{m^3} \qquad (3\text{-}9)$$

$$\varepsilon_{r\,total} = \varepsilon_{r\,CO_2} \cdot V_{CO_2} + \varepsilon_{r\,dust} \cdot V_{dust}$$
$$\varepsilon_{r\,total} = 1 \cdot 1 + 10 \cdot 5 \cdot 10^{-6} \approx 1 \qquad (3\text{-}10)$$

As easily can be seen, the dust load in the gas area does not influence the capacitance of the gas area significantly.

Scenario 3: Continuous and Pulsating Voltage Supply
The capacitors of the precipitator are energy stores, i.e., whenever fast switching voltages occur, the time constants of the resistor-capacitor-circuits have to be considered; further on the time behavior of the discharger is relevant.
Therefore the equivalent circuit diagram of the electrostatic precipitator shall be regarded in concern to its time-relating behavior (Figure 3-10).

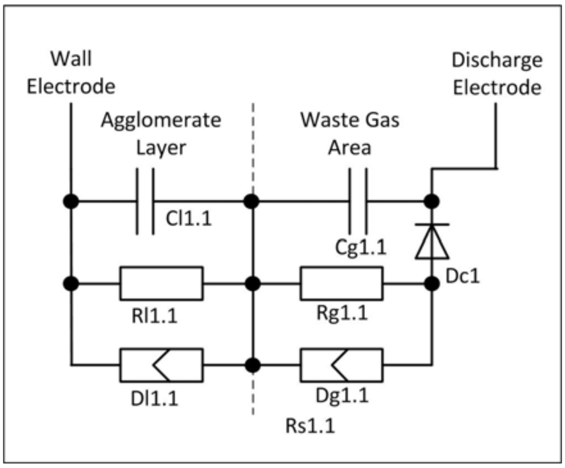

Fig. 3-10: The network in an infinitesimal small area

For a quantitative consideration of the behavior of this network, there is made up a simulation with electrical values are adjusted as listed in Table 3-2.

Parameter	**Value**	**Unit**
Area	1	m²
Electrode distance	20	cm
Permittivity of Dust	1 ... 10	
Resistivity of Dust	10^7 ... 10^{13}	Ωcm
Dust Layer Thickness	0,1 ... 2,8	cm
Gas Area Capacitance	$4{,}5e^{-4}$ ... $5{,}2e^{-4}$	nF
Layer Capacitance	0,9 ... 0,003	nF
Gas Resistance	$85e^6$ ... $100e^6$	Ω
Layer Resistance	100 ... $2{,}8e^9$	Ω
Voltage	100	kVp
Pulse Cycle	12	ms
Pulse	1 ... 9	ms
Rise Time	1	ms
Fall Time	0,1 ... 2	ms

Tab. 3-2: Parameter settings for the simulation of electrical ESP behavior; the values for the permittivity range bases on table 3-1, the values for the resistivity range base on [13]; the values for the capacitances and resistances depend always from the parameter "Dust Layer Thickness" and have to changed simultaneously

The simulation is made with some edge values for the parameters. The interesting result value is the voltage over the resistor (and capacitor) of the waste gas area, as this voltage is the potential for the electrical field force and shall be kept as high as possible.

Test 1: Carried out with DC voltage, 0,9nF layer capacitance and 100kΩ layer resistance (dust layer thickness 0,1cm). The voltage over the gas area is about 100kV.

Test 2: Carried out with DC voltage, 0,03nF layer capacitance and 2,8MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area is about 95kV.

Test 3: Carried out with DC voltage, 0,9nF layer capacitance and 100MΩ layer resistance (dust layer thickness 0,1cm). The voltage over the gas area after 200ms is about 50kV.

Test 4: Carried out with DC voltage, 0,03nF layer capacitance and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area after 200ms is about 4kV.

Test 5: Carried out with pulse voltage, pulse length 5ms, rise and fall time 1ms, 0,9nF layer capacitance and 100MΩ layer resistance (dust layer thickness 0,1cm). The peak voltage over the gas area after 100ms is about 75kV.

Test 6: Carried out with pulse voltage, pulse length 5ms, rise and fall time 1ms, 0,03nF layer capacitance and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area after 100ms is about 75kV.

Test 7: Carried out with pulse voltage, pulse length 1ms, rise and fall time 1ms, 0,03nF layer capacitance and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area after 100ms is about 82kV.

Test 8: Carried out with pulse voltage, pulse length 1ms, rise and fall time 1ms, 0,01nF layer capacitance (reduction of permittivity) and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area is about 60kV.

Test 9: Carried out with pulse voltage, pulse length 1ms, rise time 1ms, fall time 0,1ms, 0,03nF layer capacitance and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area is about 82kV.

Test 10: Carried out with pulse voltage, pulse length 1ms, rise time 1ms, fall time 2ms, 0,03nF layer capacitance and 2800MΩ layer resistance (dust layer thickness 2,8cm). The voltage over the gas area is about 82kV.

According to the test results, as long as the dust is low ohmic, the voltage over the gas area remains high, whether the dust agglomerate layer is thin or thick rsp. the supply is a DC voltage or a pulse.
With high ohmic dusts, the influence of the permittivity rsp. of the value of the capacity on the voltage over the gas area increases besides the influence of the pulse length of the supply voltage.
Without significant influence on the gas area voltage is according to the simulation the steepness of the supply transients.

3.4 Further Research and Investigation

As can be seen in the tests before, the capacitance of the agglomerate layer on the wall electrodes has some influence on the

voltage over the gas area, especially for high ohmic dusts.
The high ohmic dusts are in general well known as the "difficult dusts", and require most sophistication for the efficiency of an electrostatic precipitator, concerning the high voltage supply.

There have been made different endeavors to solve the problem for measuring the time constant within the electrostatic precipitator [14].
In other solutions the high voltage controller simply detects the back corona inset voltage integrated in the regulation algorithms and adjusts the output behavior of the supply for an optimum output voltage [15].

For a sophisticated consideration of the electrical electrostatic precipitator behavior the capacitance values which depend on the dust composites, are essential attributes of the precipitator.

4 Conclusion and Prospect

An enhanced electrical model with additional components is introduced with this paper. The model contains beside the well known resistive attributes also the capacitances, based on the geometry of the precipitator and the permittivity of the dust composites, and a discharger model.
Both are of great influence on the dynamic, electrical time dependent behavior of the electrostatic precipitator as could be shown in some simulation results, based on the enhanced model, but contrary to the resistive attributes, which is investigated well, little attention has been paid for the permittivity and for the flashover ignition time of the dust components.
As the combustibles of a power plant become more distinguished nowadays, especially as a modern power plant has to cope with a wide area of different combustibles with very different characteristics, the research should be enhanced to those attributes of the dusts, too.
For the development of further generations of high sophisticated voltage controllers, the knowledge of as much details about the dust components would be helpful.

5 Literature

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