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Improved modelling of impulse mode ESP energization

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Abstract. Regulations to reduce air pollution give more and more strict limits for the emission. Electrostatic precipitators (ESP-s) operating with traditional DC supply voltage are often not able to fulfil the requirements, therefore lot of them needs upgrading. The DC power supply is substituted by pulse energization to obtain energy saving and better efficiency of precipitation. To provide safe, reliable and efficient operation of the upgraded ESP, several problems have to be solved. One of them is the prediction of time of safe operation of the cables and insulations. Authors applied different diagnostic methods for this purpose. Another important problem is the prediction of precipitation performance. For this purpose authors developed a numerical model of modular structure. Separate modules calculate the velocity field of the gas, the charging of particles, the back corona and dust reentrainment. By the help of the model a detailed analysis of different supply modes can be made, to obtain the best possible operation of a given electrostatic precipitator applying a certain supply mode.

1. Introduction
Upgrading of an electrostatic precipitator applying impulse mode energization is a complex task. It involves the reconstruction of the ESP channels (checking and fixing of corona electrodes, collecting electrodes), the diagnostics of existing transformers and high voltage cables, renewal of the rapping system including improving the rapping program, and producing new, impulse mode control unit for the energization of the ESP.

To obtain optimal performance, operation of the electrostatic precipitator has to be modelled for different situations. This is a difficult task regarding the large number of influencing parameters [4]. For the calculation usually a modular numerical model is used [1,2], but some of them are not suitable to evaluate precipitation efficiency in case of impulse mode energization. For example, a large number of models calculate ion space charge density distribution assuming continuous ionic current between the high voltage electrodes and the grounded ones. This assumption can lead to incorrect result when the “travelling time” of the ions and the time period of the supply voltage (and the duration of the current impulses and “current free” periods) are in the same range. However ion space charge density is important from the point of particle charging [3].

Our new model contains a method for the ion space charge density calculation that takes into consideration the rapid, time dependent processes of the impulse energization, providing more reliable results for the evaluation of the precipitation process. It also takes into consideration the rapid, time dependent processes providing more reliable results for the evaluation of the precipitation process.
2. Diagnostics of high voltage transformers and cables
During an upgrading process it has to be decided, whether the existing transformers and cables can be used with additional control device or the total system has to be replaced. For the correct decision diagnostics of high voltage transformers and cables are very important to ensure the safe operation of the ESP. In this paper we focus on the second one, the diagnostics of cables.

As during operation the physical properties (especially the electric strength) of the cable insulation are degrading. The causes of ageing are the operating stresses, e.g. temperature, electrical stress and environmental stresses, e.g. moistening etc. By the effect of the stresses an irreversible aging process arises, the change of the molecular structure of the material and by it the mechanical and the dielectric properties are changed, too. The degree of degradation of the material can be followed by chemical examination. This kind of analysis gives the most sensitive information about aging, but it is a destructive test, i.e. the samples have to be cut out from the insulation and by this the insulation will be destroyed. The most of mechanical examinations have lesser sensitivity but these need cutting out samples, and so insulation will be destroyed, too.

The non-destructive diagnostic methods are based on the measurement of the dielectric characteristics of the insulation, using lower voltage than the nominal voltage of the equipment. In this paper an overview of two methods is presented, namely the measurement of absorption current and return voltage.

When a DC voltage is connected to the insulator, a decreasing current can be measured according to Fig. 1. Resultant current contains three different components. First one \( J_c \) charges geometric capacitor to the supply voltage, this is dominant only at the very beginning. Second one \( J_p \) is because of the polarization: it is decreasing with increasing degree of polarization. A long time after the switch on, only the third component \( J_v \) remains, namely the leakage current. As the condition of the cable is getting worse, the time function of the absorption current changes. This change provides information about the expected life of the cable.

Another non-destructive method is the measurement of return voltage. Connecting high DC voltage for the insulation for a long time, the polarization can be completely developed. Then applying a short circuit at the input, the geometrical is discharged immediately, but the polarization can not change so rapidly. Therefore opening the short circuit after 1 – 2 seconds, the geometrical capacitance is recharged by the remaining polarization. The voltage appearing at the output is called return voltage, its starting slope of its time function is characteristic for the material [5]. (Fig. 2)

**Figure 1.** Components of absorption current  
**Figure 2.** Return voltage: \( E \): electrical field intensity inside the insulator; \( P \): degree of polarisation; \( i \): absorption current \((i_v \): leakage current)
In the reconstruction work of an ESP in a power plant both methods were used. Measurement results showed that the four out of six applied high voltage cables in the ESP unit are available for the further operation and two cables are required to replace.

3. Modelling of pulse energization

Regarding that the upgraded ESP uses pulse energization, it is important to make the numerical model suitable to handle changing voltage of the electrodes. The most critical part of the computation from this point of view is the determination of the ionic space charge density distribution.

In our model the donor cell method is used to determine the ion space charge in the ESP half channel [6]. The advantage of this method is the use of an irregular (non equidistant) grid division. So the focus can be on parts of the ESP channel where changes are relevant, and other parts, where physical values not much differ, can be out of focus to fasten the calculation.

The equation \( \text{div} J = 0 \) is valid for each cell in the grid, so the number of charges entering a cell, equal the number of charges leaving the cell. The current density in a cell is proportional with the ion mobility in the cell \((\mu)\), with the charge density in the adjacent cells \((\rho)\) with the potential between the adjacent and the current cell \((\phi_j - \phi_i)\), and inversely proportional with the distance of the cells \((\Delta_{j,i})\) which is the distance between the midpoints of the cells.

\[
J_{j,i} = \rho_j \cdot \mu \cdot \frac{\phi_j - \phi_i}{\Delta_{j,i}}
\]

By the charges leaving the cell the charge density of the cell is taken into consideration.

\[
J_{k,i} = \rho_i \cdot \mu \cdot \frac{\phi_i - \phi_k}{\Delta_{k,i}}
\]

If we complete the equation \( \text{div} J = 0 \) with the charge loss coming from the recombination of the charge carriers, we get the equation

\[
J_{j,i} \cdot L_{j,i} + J_{k,i} \cdot L_{k,i} + J_{l,i} \cdot L_{l,i} + R_i \cdot A_i = 0
\]

where \( R_i \) means the recombination factor for the charge carriers. The solution of the linear equation system gives the ion space charge in the ESP half channel.

To follow the change of ion space charge density in time, it is necessary to modify the donor cell method into a time-dependent form [6]. It means that instead of the balance of currents (or current densities) of the donor cell, the balance of transported charge has to be determined. For this purpose a time step \( dt \) is introduced, to obtain a charge amount (as a multiplication of the current and the time step) flowing into and out from the cell. With this procedure, the change of ion charge can be monitored inside the cell as a function of time.

Time step \( dt \) is chosen to such a value, which is significantly below the "residence time" of a charge carrier inside a specific donor cell. This requirement can be fulfilled, when the time step is less than the shortest side of the donor cell \((ds)\) divided by the product of ionic mobility \((\mu)\) and electric field strength \((E)\):

\[
dt << ds / (\mu E).
\]

The previously described method requires the modification of the process of calculation as well as the data structure of the model. A new set of data has to be added to the existing data structure storing the initial ionic charge density

1. calculation of the electric field with the initial ionic charge density
2. calculation of currents according to the donor cell method
3. determination of charge transfer during time interval \( dt \) using the initial ion charge density values
4. calculation of actual ionic charge density
5. replacing initial ionic charge density by the new one and going back to step 1.
4. Analyzed arrangement

The analyzed electrostatic precipitator is wire-plate type, the distance between plates 20 cm. It contains of 3 zones, each zone has separate rapping program and voltage source. For the analysis the same pulse energization was applied in the zones. The voltage peak was controlled below the arc voltage, as a typical value, 70 kV peak was selected. Particle size distribution was substituted by 0.2;0.5;1 and micron fractions, velocity of gas at the inlet was 1 m/s, resultant input concentration 100 g/m³. For the specific resistance $10^9 \, \Omega \cdot \text{cm}$ was selected.

Visualisation of the computation results can be seen in Figure 3. It represents a moment after some seconds the entering of dust load into the precipitator. Upper part of the figure represents the potential distribution inside the half-channel. Second part shows the average velocity distribution, while the remaining parts are representing the distribution of dust concentration, for the total dust amount, for the 0.2, 0.5 and 1 micron fractions. Continuing the calculation until steady state, an overall dust emission below 6 mg/m³ can be obtained, that is in a good correlation with the measurement results.

Figure 3. Voltage, velocity and concentration distribution inside the ESP (total concentration and concentration of components)

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