DIFFERENT TYPES OF DUST RESISTIVITY

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Abstract: It is generally accepted that dust resistivity in excess of $10^{11}\ \Omega cm$ leads to the formation of back corona and to a deterioration of ESP performance. Besides dust conditioning, the most popular approach for reducing problems with back corona is the application of pulsed corona systems.

The idea behind pulsing is very simply to reduce the E-field within the dust layer by reducing the time-averaged current density. However, experience shows that other high resistivity cases are resolved successfully with an opposing approach, using especially smooth HV from three-phase rectifiers in combination with high current densities.

A detailed investigation into this discrepancy has revealed that high values of dust resistivity can be traced back to at least two different mechanisms.

“Standard” high resistivity dusts show the behaviour which is typical for dielectrics. High potential drop across the dust layer is produced by the injection and immobilization of charge carriers into the material. Resistivity is strongly dependent on time and corona polarity and inversely proportional to the root of current density. The dust layers reach a high level of space charge density.

In a sample of an “untypical” high resistivity dust we found that resistivity is independent of layer thickness and of corona polarity and does not show time effects. The dust layer does not accumulate any significant amount of space charge. The potential drop across the dust layer is nearly independent from current density, resulting in a resistivity which is inversely proportional to current density. With very high E-fields, the dust layer shows a progressive increase of current uptake with time, ending in a breakthrough. All these are the typical characteristics of a varistor material.

Our results show that different mechanisms of high dust resistivity do exist. Therefore an appropriate choice of the high voltage supply and its control should be based on a thorough analysis of the electrical properties of the dust. A clearly better separation efficiency will be achieved.

KEYWORDS: Dust resistivity, Back corona, Pulsing, Three-phase rectifiers, Dielectrics, Varistors.

1 Introduction

It is generally accepted that dust resistivity in excess of $\mathbf{10^{11}}\ \Omega\boldsymbol{cm}$ leads to the formation of back corona and to a deterioration of ESP performance.

So far, high dust resistivity was seen as a one-dimensional problem. Besides a direct modification of dust resistivity by dust conditioning, a standard approach to reduce problems with back corona was and is pulsed corona operation [Porle 1985], [Hall 1990], [Parker 1997].

More recent experience on the industrial scale [Schmoch & Stackelberg 2018] has shown that some cases of back corona do not respond well to pulsed operation, while much better results are obtained by applying smooth HV and increased current density by use of 3-phase TR sets. However, the practical success with 3-phase TR sets is in a direct contradiction to the common theoretical understanding of back corona.

In a cooperation between the authors, this puzzle was solved by a detailed investigation on the dust properties for a specific case. As a result, we found a new, so far unknown mechanism of high dust resistivity. On one hand, the existence of different physical mechanisms behind high dust resistivity explains that different technical actions may be required to overcome the problem. On the other hand, this example also shows that more complex dust resistivity measurements in the lab can be necessary for providing a correct problem analysis.

2 State of Knowledge

Generally, resistivity $\boldsymbol{\rho_{el}}$ is defined as the ratio between the E-field E inside a material and the current density $\boldsymbol{i}$ flowing through the material:

$$\boldsymbol{\rho_{el}} = \frac{\boldsymbol{E}}{\boldsymbol{i}} \tag{1}$$

Going to a sample of material with a thickness s and an area A, resistivity is determined from the current I passing through the sample when a voltage U is applied:

$$\boldsymbol{\rho_{el}} = \frac{\boldsymbol{U\,A}}{\boldsymbol{s\,I}} \tag{2}$$

Considering the E-field inside the dust layer, we find the relation:

$$\boldsymbol{E} = \boldsymbol{\rho_{el}}\frac{\boldsymbol{I}}{\boldsymbol{A}} = \boldsymbol{\rho_{el}}\,\boldsymbol{i} \tag{3}$$

Assuming that resistivity is a material constant (which corresponds to assuming ohmic dust properties), we see that the E-field inside the dust layer should be proportional to the current density. According to a simple approach, disturbances of dust precipitation by back corona will occur when the E-field inside the dust layer surpasses a critical value E_{crit}. Different authors give different values, but mostly an E_{crit} in the range between $10 - 30\ kV/cm$ is found [Wiggers 2007]. The value of $32\ kV/cm$ corresponds to the dielectric strength of air at ambient conditions. At higher E-fields, so the simple theory, the gas inside the dust layer will have an electrical breakthrough. A crater will be formed, and the E-field across the dust layer will be sufficient to establish a luminous corona discharge inside the crater. E_{crit} appears to depend the pore structure of the dust cake. Notably with very fine dusts, much higher values of E_{crit} have been found [Aleksin et al. 2016], [Bürger & Riebel 2021]. The increased dielectric strength of the gas within fine dust layers is explained from the Paschen law. While the classical type of back corona is associated with crater formation, other types of back corona without crater formation have been reported as well [Masuda in Parker 1997], [Bürger & Riebel 2021].

Dry ESPs separating dust particles from a gas flow require a specific range of dust resistivity to reach a good overall performance. The impact of dust resistivity on the separation efficiency of an ESP is shown in **Fig. 1**. The effective particle migration velocity (as derived from the overall efficiency using Deutsch equation) drops from ~15 to ~5 cm/s when the resistivity increases from 10^5 to 10^{11} Ωcm [Parker 1997]. To compensate this reduced migration velocity, the volume or (equivalent) the collecting surface of the ESP must be increased by a factor 3. Because of this strong impact a precise measurement or prediction of dust resistivity is essential for ESP sizing.

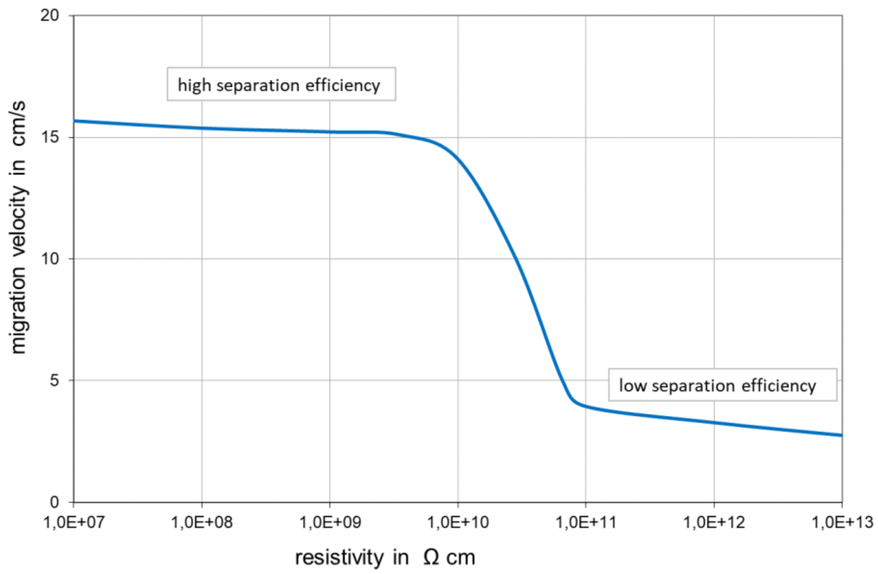

Fig. 1: *The impact of dust resistvity on separation efficiency [Parker 1997].*

2.1 Measurement of Dust Resistivity – State of the Art:

The definition of resistivity given by Eq. (2) also is the basis of the experimental arrangement which is typically used for resistivity measurements (**Fig. 2**). For obtaining realistic measurement data, the temperature and the condition of the gas atmosphere (humidity, trace gases such as SO_2, HCl, NO_x) must be controlled carefully. Therefore, measurements are executed in measurement chambers with controlled temperature and gas atmosphere, while the electrode contacting the sample must be permeable in order to allow continuously the establishment of an adsorption equilibrium between the sample and the gas atmosphere.

As an outcome of such measurements, dust resistivity can be plotted as a function of temperature and humidity. **Fig. 3** shows a typical result. Depending on the volume conductivity of the dust material and on the adsorption of trace gases, the maximum of resistivity is typically found in the temperature range between about 150 °C and 250 °C.

Measurements of resistivity, of course, have to follow exact boundary conditions: the thickness of the dust layer, its temperature and humidity, the range of current density, the time lapse between applying the voltage and reading the current etc. should follow a well-defined and documented procedure.

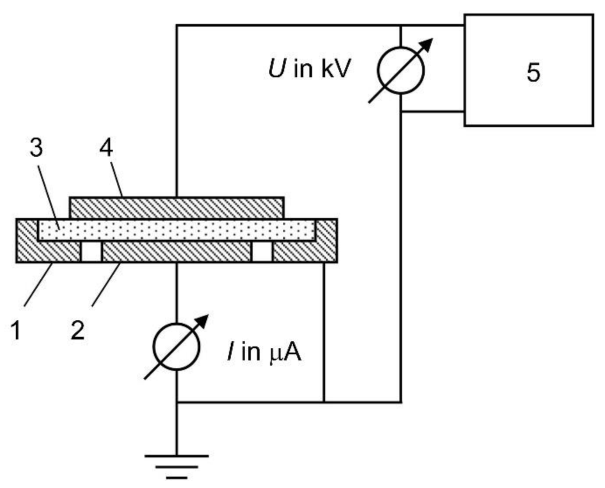

Fig. 2: *Measurement of dust resistivity, example [VDI 3678]*

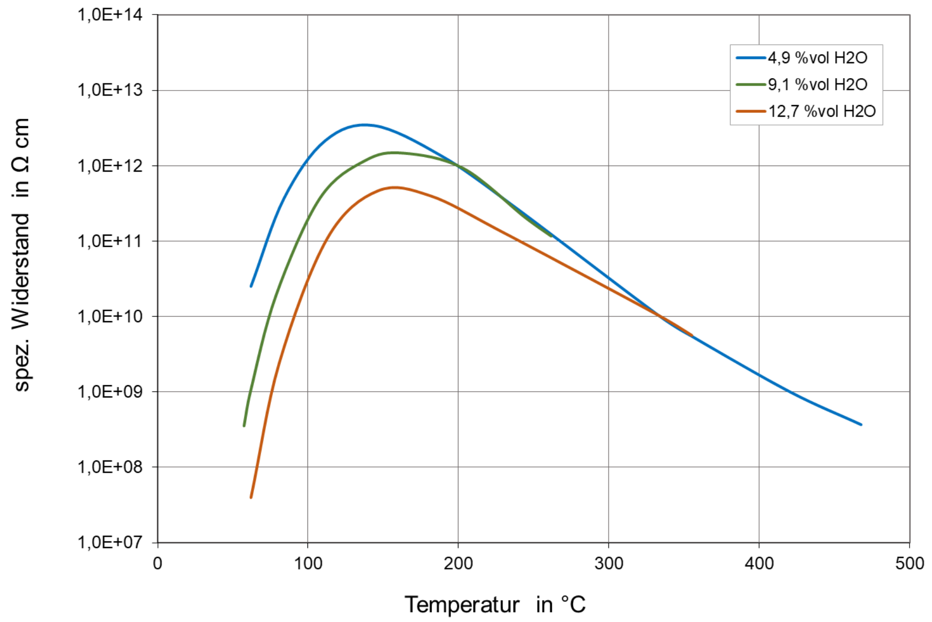

Fig. 3: *Example of specific dust resistivity depending on temperature with gas humidity as a parameter. [Oglesby & Nichols 1987]*

In an electrical field of an ESP, however, the voltage, the temperature and humidity of gas are constant, only. All other parameters, including the particle material, vary. The thickness of the dust layer decreases from inlet to outlet and increases from top to bottom, the specific current and the development of field strength change from place to place. Finally, all parameters are continuously changing over the time due to operational conditions at the inlet and the control of the high voltage supply.

This means that sizing an ESP includes always the transfer from measured dust resistivity to operational values. In former times this correspondence had to be found for ESPs operated with a 1-phase TR set. Actually, more divers HV supplies are on the market, including high frequency switched mode power supplies, 3-phase TRs, intermittent energization, micropulsing supplies and others. At the moment, it is not clear in which way the resistivity measurements react to the type of power supply used for the measurement. But the experience with 3-phase TRs which is described here indicates that more attention must be given to this point in order to reach a reliable way of ESP sizing.

2.2 Non-Ohmic Characteristics of Dust Resistivity – Dielectric Dust Type

While many of us still understand dust resistivity as a well-defined, dust-specific parameter, the reality is much more complex. Indeed, the behaviour of dusts with a lower resistivity follows Ohm´s law quite closely. However, all dusts having high resistivity are showing non-ohmic characteristics which can be very pronounced.

Parallel to the deviations from ohmic behaviour which can be found from resistivity measurements in the lab, also the experience with back corona both in the lab and in large-scale applications indicates non-ohmic dust properties. Numerous reports agree in that back corona starts only after some time of ESP operation or with an increasing thickness of the dust layer [White 1974], [Chang & Bai 1999], [Ni et al. 2016].

More detailed measurements on typical dusts show that dust resistivity depends on the current density [Wiggers 2007], which explains why resistivity measurements should be done with a current density which is comparable to the real situation. Further detailed investigations have shown that the properties of highly resistive dust layers basically correspond to the typical properties of dielectric insulation layers [Aleksin, et al. 2016], with the following characteristics:

- During electrostatic precipitation or during resistivity measurement, highly resistive dust layers take up a lot of electrical space charge. Charge carriers (free electrons and holes) are injected from the corona discharge and/or from the contact with the electrodes. Typically, the surface of the dust layer has the same polarity as the corona discharge, while the base layer on the precipitation electrode acquires the opposite polarity.

- Resistivity shows a very pronounced increase with time. Typically, a more or less linear relation between log of resistivity (or current) over log of time is found, see **Fig. 4**. This increase is explained by an increasing number of immobilized charge carriers accumulating inside the dust layer.

- Even though the dust layers always are bipolar, one polarity can dominate, depending on the conditions of charge injection (by contact with the electrode, or by gas ions). In case of a non-symmetric contact (e.g., in a corona discharge or with different electrode materials), resistivity can depend on polarity.

- Resistivity measurements with contacting electrodes (as shown in **Fig. 2**) typically give lower resistivity values compared to measurements in a corona discharge. This is explained by the fact that with corona charging, the space charge inside the dust layer is biased towards the polarity of the corona. The nearly unipolar space charge situation resulting from this produces stronger E-fields inside the dust layer and a higher voltage drop across the dust layer.

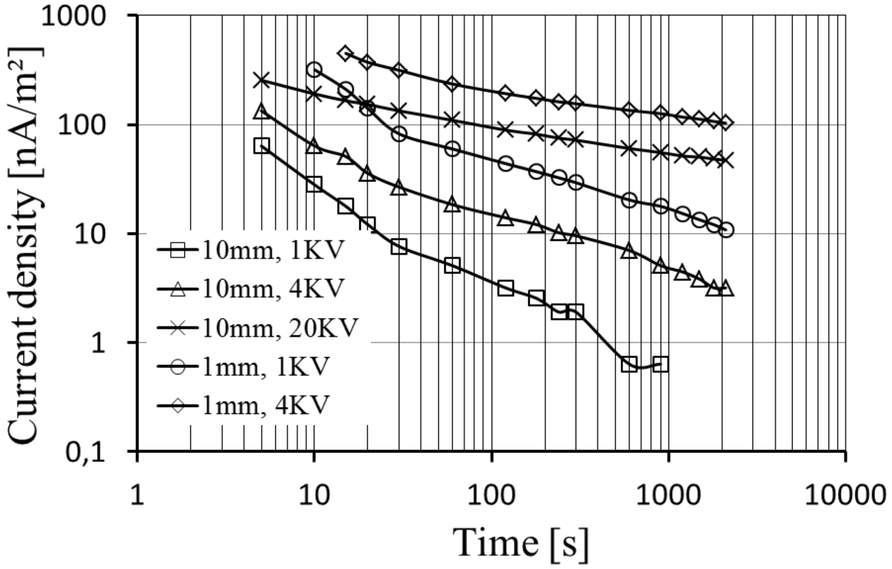

Fig. 4: *Current density through samples of a highly resistive dust (DEGALAN®) as a function of time [Aleksin et al. 2016]. With an increasing E-field across the dust layer, the immobilization of charge carriers is less pronounced.*

- Resistivity is inversely proportional to the root of current density. A 100-fold increase of current density leads to an approximately 10-fold decrease of resistivity.

- Deviating from Ohm´s law, resistivity typically increases with increasing thickness of the dust layer. Simplified theoretical approaches (based on the assumption of unipolar space charge inside the layer) predict a proportionality of resistivity to the square of layer thickness. Experimental results can vary in a rather wide range.

2.3 The Concept of Pulsed Corona Operation

Pulsed corona operation is practised in a number of different variations [Porle 1985], [Hall 1990], [Reyes in Parker 1987]. The common idea behind is to stay below corona onset voltage for a large fraction of the time, while corona operation with the combination of gas ion generation and particle charging takes only a smaller fraction of time. In this way, the time-averaged current density is reduced significantly, and with it also the E-field inside the dust layer. Assuming a smooth DC current in combination with dielectric material properties, a reduction of current density by a factor of 100 should lead to a reduction of the E-field by a factor of 10.

In case of micropulsing, voltages well beyond the DC sparking voltage can be applied for very short periods of time. This equipment needs two parallel and coordinated transformers, which produce a combination of high current density and high E-field during the pulse in a very short time of some 80 µs. With micropulsing, the range of dust resistivities which is accessible for ESP operation may be extended by about two orders of magnitude, reaching values of around $10^{13}\ \Omega\ cm$ [Porle 1985], [Reyes in Parker 1997].

Intermittent energization or semipulsing uses pulses with a duration in the order of a halfwave (10 ms). Semipulsing is achieved very economically by switching the AC supply voltage going into the transformers, but also has a lower potential for reducing back corona.

2.4 The Concept of Low Frequency AC Corona Operation

Another concept which is based on the theory of dielectrics was developed by Aleksin et al. (2017). The basic idea departs from the fact that dust resistivity is time dependent. Initially, as long as the dust layer does not contain too many immobilized charge carriers, resistivity has low values. But within several seconds of ESP operation, charge carriers are immobilized inside the dust layer, building up an immobilized space charge. In parallel, the dust resistivity increases and may reach the critical range. When the polarity of the discharge is reversed, also charge carriers of opposite polarity are moving into the dust layer. Now mobile charge carriers of the new polarity are attracted to immobilized charge carriers of the previous polarity. The charge carriers recombine and the previously immobilized space charge disappears. Thus, the dust resistivity is kept on a low level for a short time, until a new immobilized space charge with the new polarity is built up.

With a period of polarity reversal in the range between 10 s and a few 100 s, dusts with resistivities going up to $10^{16}\ \Omega\ cm$ were precipitated successfully. However, in the resistivity range above $10^{14}\ \Omega\ cm$, the adhesion of the dust layers to the precipitation electrodes was extremely strong, and dust layer removal was a difficulty.

2.5 The Concept of 3 Phase Transformer/Rectifier Sets

The basic design rules of a 1-phase and a 3-phase TR set are similar. As for the 1-phase TR set the size of the 3-phase set can easily be adapted to the size and requirements of each individual ESP. But the quality of secondary voltage and current are rather different (see **Fig. 5** and **Fig. 6**).

It can be seen that the 1-phase TR set produces a direct voltage with a percentage ripple of some 30 %; under partial load conditions even more. The 3-phase technology, however, provides a direct voltage with some 3 % percentage ripple in a wide load range [Schmoch & Steiner 2022]. The voltage curve is proportional to the current which goes from the discharge to the collecting electrode of the electrical field.

In the examples discussed, each of the three phases is rectified and controlled separately and the design allows a pulse mode operation of the 3-phase TR set, similar to the 1-phase TR set. Other designs of 3-phase TR sets provide other features.

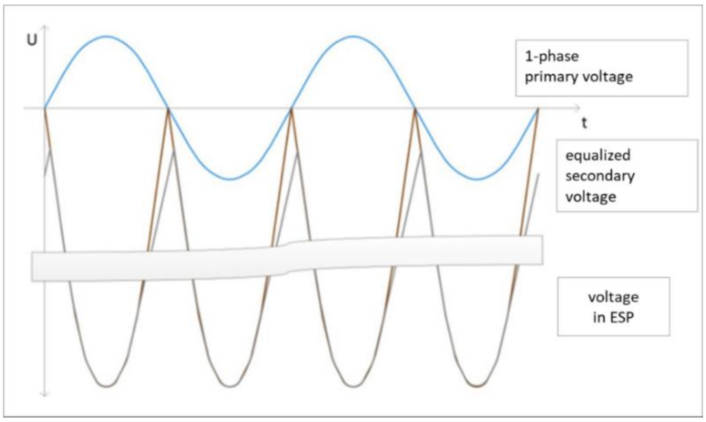

Fig. 5: *Secondary voltage from 1-phase TR set*

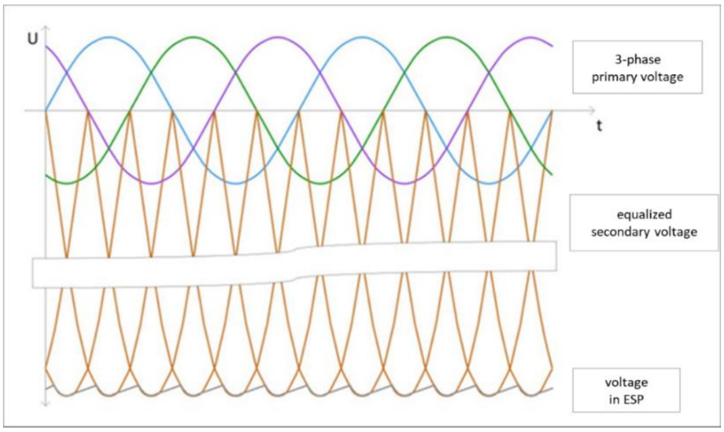

Fig. 6: *Secondary voltage from 3-phase TR set*

3 Recent Experience with Precipitation of Ore Sintering Dust

Here we report some practical experience with a dust collected downstream a sinter strand for Iron Ore Sintering (in short, IOS dust). An ESP installed in this situation was suffering from back corona. Following "state of the art" knowledge, pulsed ESP operation was established, but was in fact not helpful to improve the situation. In contrast, the installation of a 3-phase TR set was a clear success [Schmoch & Stackelberg 2018].

In a discussion between the authors, we found that the success with the 3-phase TR set was in a total contradiction to all theoretical knowledge about the mechanisms of back corona formation and remediation with highly resistive dusts of the standard type, that is, with dusts showing dielectric behaviour. This led to the suspicion that we might have to do with a dust showing untypical properties. In a detailed laboratory investigation on the dust properties, this suspicion was confirmed.

In the following, we are going to present the original experience with the IOS dust, the results from the laboratory investigations, and a discussion on further effects which may arise from the application of 3-pase TR sets.

3.1 Observations with Industrial ESPs for Iron Ore Sintering Dust

Several years ago an ESP downstream a sinter strand for Iron Ore was equipped with 3-phase TR sets. Compared to the micro pulse system which was previously used in this application, the 3-phase TR (abbreviated as 3TR) set supplied a higher average level of current input and also under partial load conditions a smooth DC with tiny ripples. In short, 3TR is an approach which produces a situation which is quite exactly the opposite of pulsing or intermittent energization (**Fig. 6**).

Surprisingly the 3TR equipment worked far better than the previously applied micropulser. Instead of some 20 mA per field, now about 1200 mA could be brought into the field; the clean gas dust content dropped from 40 mg/Nm³dry to less than 10 mg/Nm³ dry, if we compare the operation of two similar ESPs. Tests showed that the improvement can be observed both for a higher operational temperature of some 160 °C and for a lower flue gas temperature of some 110 °C.

Fig. 7 gives more information obtained with another installation featuring 3TR sets with optional semipulsing. It shows the operation of the IOS ESP during two hours. The volume flow (light brown line) and the temperature (dark brown line) are almost constant. The flue gas temperature of about 167 °C (log. scale!) must normally be considered as a level of very high resistivity. The green lines indicate the current level moving up to more than 1000 mA per electrical field. The voltage ranges (blue lines) at some 47 kV on rather a constant level.

The red line shows the development of the clean gas dust content. It is an opacity signal directly downstream the ESP. It is not the official, calibrated signal at the stack, which is below 10 mg/Nm³ dry. The interruption at about 12:15 h is due to an automatic calibration.

According to this signal the stationary clean gas dust drops to some 20 mg/Nm³, as long as the TR sets are working in continuous mode, i.e. with an almost straight DC supply. At the pink vertical dotted line the operational modes of the TR sets are switched to semipulsing mode: one half wave package - corresponding to 10 ms - is pushed to maximum voltage, whereas the next two half waves are switched off (20 ms). This operational mode was used to simulate the operation of a 1-phase TR set, as under these conditions the correspondence between operational and measured dust resistivity is best from experience.

At pulse mode operation and with "conventional" high dust resistivity, the clean gas dust content would be expected to reduce slightly or, at medium dust resistivity, the clean gas dust content would be expected to creep slowly a bit to a higher level. But here the mechanism obviously was completely different: the dust content went up within seconds. After a short time this process had to be interrupted thus avoiding environmental trouble.

As soon as the continuous mode was switched on again, the clean gas dust content drops rather fast down to a certain level in between. Then it decreased gradually to the original value of 20 mg/Nm³. Remarkably, the current increased steadily up to more than 1000 mA (≈ 0,35 mA/m²), the clean gas dust content going down in parallel. The voltage, however, was almost constant on one level of some 47 kV. With micropulsers on the same field a current of < 20 mA (< 0,007 mA/m²) would be possible, only.

Fig. 7: *Clean gas dust content (red line) with smooth DC from a 3-phase TR set. Interruptions through short pulse mode operation times at about 11:40 h and again at 12:35 h.*

This observation of ESP behaviour during a period of two hours corresponds with the behaviour during only some 20 s of operation, **(Fig.8)**. After a spark the control pushes the voltage back to a predetermined level and is directed to stay on this constant level for a while. The corresponding current follows with slight delay: the capacities are "filled". From this time on it is necessary that the current creeps up steadily. Finally the process ends in a further spark.

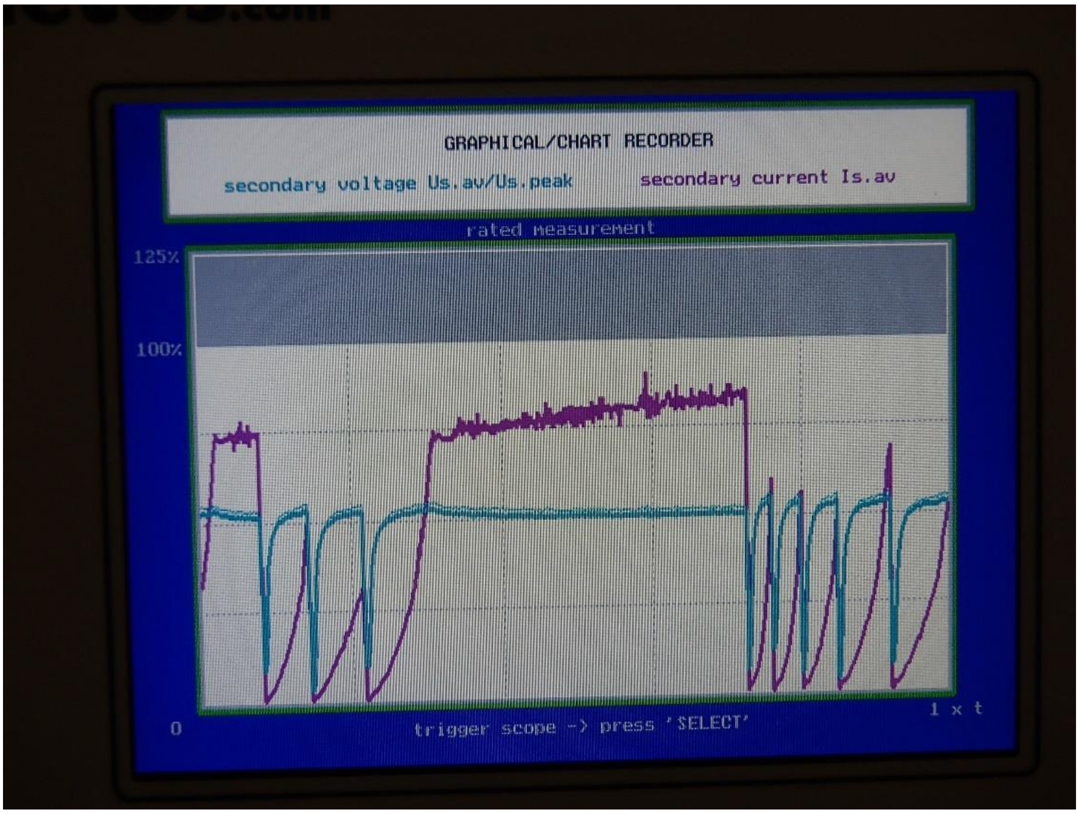

Fig. 8: *Constant controlled voltage (light blue) and slow shift of current. The time scale is 5 s per unit.*

This or a similar development can be observed again and again. From this we derive two consequences :

- The control must allow a current creeping up at constant voltage. This means the voltage is clearly the leading parameter and it is measured as true voltage. The cheaper way to interpret the measurement of current as indication for the voltage does not allow the observed development. An increasing current would be interpreted as increasing voltage.

- The increasing current indicates that the resistivity of the dust layer is going down gradually. Due to this effect the driving voltage for the transfer of the current through the dust layer decreases and at constant voltage given by the 3TR, the voltage between discharge electrode and surface of the dust layer increases. Hence the current from the discharge electrode to the surface of the dust layer becomes bigger.

This effect could not be observed with 1-phase TR sets, as the ripples of the DC on the secondary side seem to be too dominant.

The strong impact of different types of TR sets makes it necessary to better understand the physics behind this effect. This knowledge can be used to improve the ESP performance by the selection of the appropriate type of TR set.

3.2 IOS Dust Resistivity Showing Varistor Characteristics.

The IOS dust characteristics were measured using a set-up similar to the one shown in **Fig. 2**. For more realistic conditions, however, the dust resistivity was measured from the insertion loss (voltage difference for a given current value) into a corona discharge. Following the conditions in the industrial process, dust resistivity was measured at two different combinations of gas temperature and water dew point: 110 °C/ 38 °C or 160 °C/ 40 °C. The gas inside the measurement chamber was exchanged continuously at a rate of 1 ltr./min in order to avoid the accumulation of NOx during the measurements. The dust layer thickness was mostly 3 mm, as the dust was not sufficiently fine and homogeneous for a reproducible production of 1 mm layers.

In the first place, we found that the dust resistivity does not show significant time effects. This is shown in **Fig. 9**. Within the time resolution of the instrumentation (which is about 1 s), we do not find any significant change of current uptake after applying the voltage as far as the E-field remains in a moderate range (here, up to 8 kV/3 mm = 27 kV/cm). This is in a big contrast to the experiments with a "typical" dust in a comparable range of resistivity as shown in **Fig. 4**. Time effects are found only for the case that the IOS dust is exposed to very strong E-fields. In this case, most of the measurements show an increase of the current, followed by a stabilization after some time.

Nevertheless, we find that the IOS dust is changed permanently when strong fields have been applied. This is shown for the example of the measurements with 5 kV. When 5 kV is applied for the first time (following the measurement with 4.8 kV), the current density is at $10^{-9}\ A/cm^2$. When the 5 kV are applied again (following all the other measurements going up to 11 kV), the current density has risen to the 50-fold, that is to about $5 \cdot 10^{-8}\ A/cm^2$.

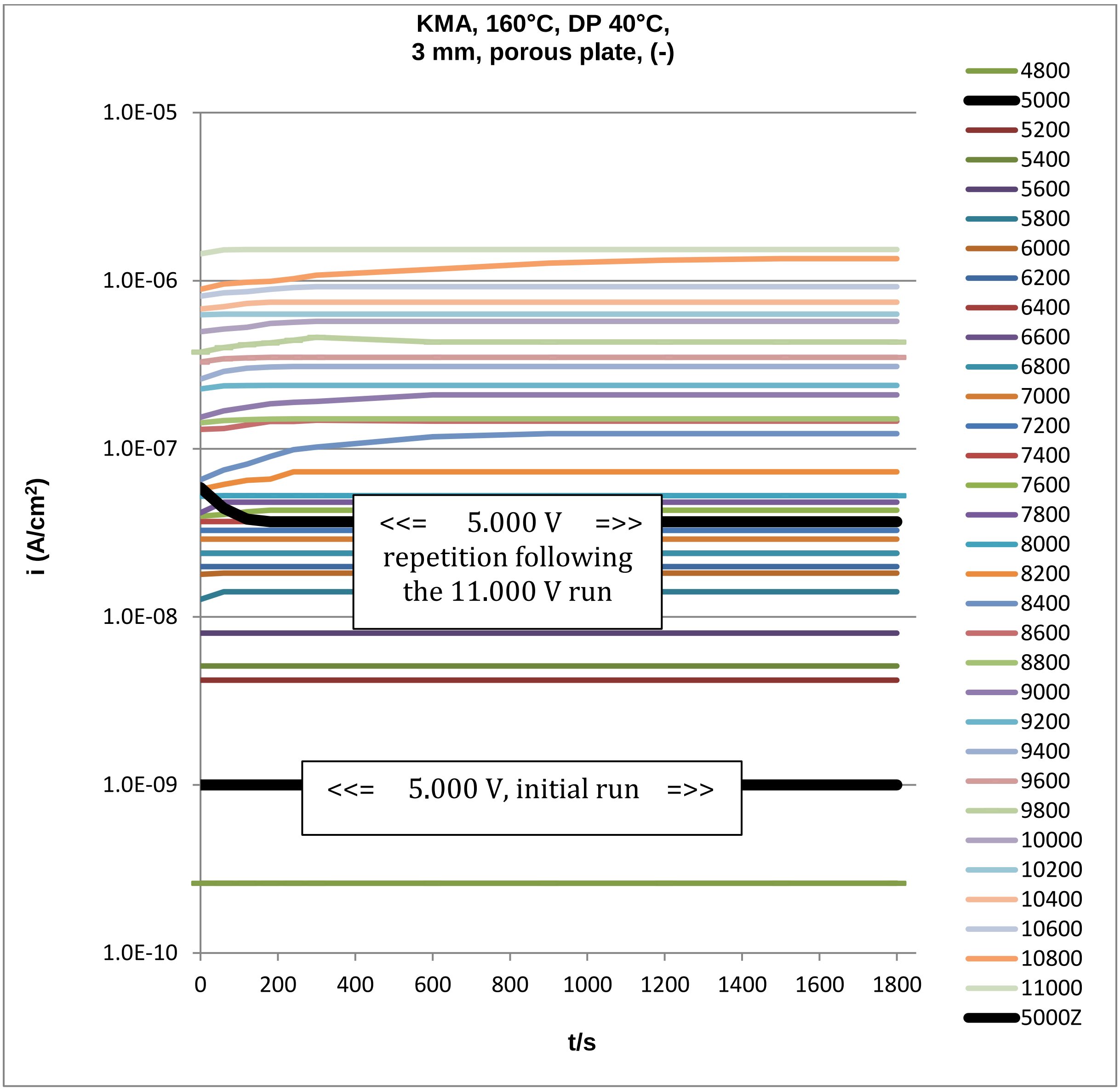

Fig. 9: *Current density through a 3 mm layer of IOS dust as a function of time for different voltages. The experiment was started with the lowest voltage proceeding to the higher voltages. In the end, the 5.000 V measurement was repeated, which resulted in a 50-fold increase of current density compared to the initial 5.000 V measurement (fat black lines).*

In the second place, we find that the resistivity decreases with increasing current density. This is illustrated in **Fig. 10**. Whereas we have $\boldsymbol{\rho_{el} \sim i^{-0.5}}$ in the case of the dielectric type dusts, we find a much stronger decrease and a proportionality of $\boldsymbol{\rho_{el} \sim i^{-1}}$ in case of the IOS dust samples. In other words, the dust layer shows a breakthrough behaviour with a very strong increase of current density when a certain E-field is surpassed.

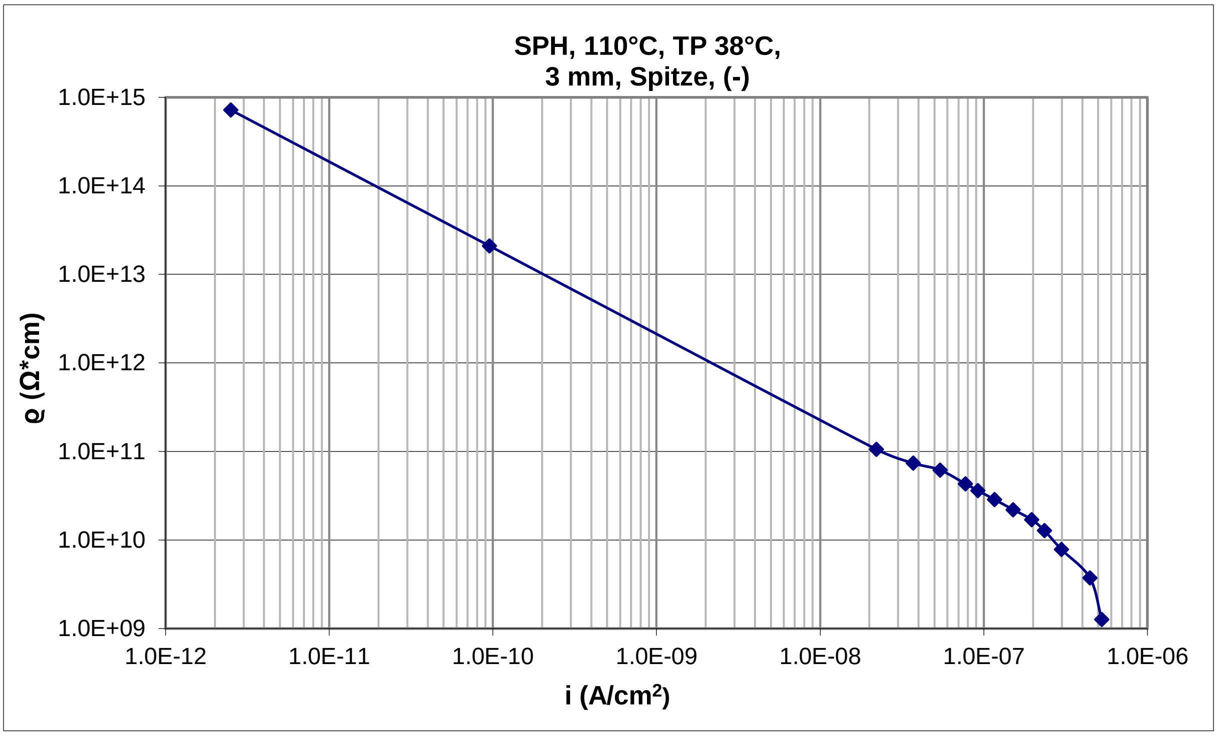

Fig. 10: *Dependence of IOS dust resistivity on current density. Here we see results from a typical measurement executed with negative corona polarity on a 3 mm dust layer. The full breakthrough occurs at a current density of just below* $0{,}001\,mA/cm^2 = 10\,mA/m^2$.

Further important characteristics are, that the dust resistivity seems to be independent from the polarity of charge carriers in the corona discharge, on applying the E-field via a corona or via electrodes contacting the layer, and on the thickness of the layer.

All of these characteristics which we have found with the IOS dust correspond to the characteristics of varistor materials as they are used for the fabrication of electronic devices [Clarke 1999]. The physical background of varistor behaviour is that the resistance originates mainly from electrostatic potential barriers at grain boundaries or crystallite boundaries, whereby the current transport across these barriers is controlled by thermionic emission.

4 Discussion: Dust Resistivity Type and Back Corona Countermeasures

The industrial experience with the electrostatic precipitation of the IOS dust had shown an unusual behaviour with respect to the occurrence of back corona. While a reduction of the current density by pulsed energization was not able to improve the situation, the application of a 3-phase TR set with increased average voltage and increased current proved to be much more successful.

Both the failure of pulsed operation and the success with the 3-phase TR set can most probably be explained with the unusual, varistor-type dust properties which are described here for the first time.

Due to the proportionality $\boldsymbol{\rho_{el} \sim i^{-1}}$ the IOS dust reaches extremely high dust resistivity when the current density is reduced by pulsing, while the E-field inside the dust layer is unchanged. Hence pulsing cannot help to reduce the E-field inside the dust layer significantly.

In contrast, the application of sufficiently strong fields leads to a breakthrough of the IOS dust layer and to a permanent reduction of the layer resistivity.

An additional effect from the application of the 3-phase TR set might be that significant amounts of ozone and nitric oxides are produced when high current densities are applied. Ozone can oxidize SO_2 to produce SO_3 and finally H_2SO_4. Both H_2SO_4 and NO_x or HNO_3 can adsorb to the dust and reduce dust resistivity. So we may have some kind of chemical dust conditioning which is driven by the application of high current densities.

5. Conclusions

The present contribution has shown evidence that different types of highly resistive dusts do exist, which also require different technical approaches to reduce back corona.

Typically, highly resistive dusts follow the characteristic properties of dielectric materials. As a counterpart to this, we have found and characterized an example of an iron oxide dust showing the characteristics of a varistor material.

Experience from the industrial application has shown that pulsed corona operation fails to reduce back corona with varistor-type dust. Meanwhile the opposing approach – the application of smooth DC voltage from a 3-phase TR set with high values of average voltage and current – proved to promote current take-up and reduce particle emission. This experience is supported by laboratory measurements which approve that the resistivity of the varistor-type dust can be changed permanently in strong E-fields.

As a result, we see that a more detailed characterization of highly resistive dusts would be helpful to find the right answer to fight back corona problems.

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