

# More than 20 Years Practical Experience with Switched Mode Power Supplies in Modernization Projects

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## 1 Summary / Abstract:

In the development of switched mode power supplies (SMPS) different topologies and power devices have been used to provide optimum power supply for electrostatic precipitators (ESP). Different generations of SMPS will be shown below. More than 20 years after the development of the first SMPS for electrostatic precipitation, sufficient experience in improvement of performance has been collected due to many operating ESP applications. With pre-tests and test installations the potential for improved collecting efficiency can be identified before SMPS are permanently installed. Conducted modernizations have shown remarkable ESP performance increase. The typical installations of SMPS at the gas inlet fields tend to provide synergy effects for better performance even in the subsequent fields. However, the degree in increase of achievable collecting efficiency depends on the process conditions. In particular, proper mechanical state of the ESP is essential for optimum performance.

Keywords: SMPS, IGBT, power semiconductors, pre-test, test installation, history, space charge, corona suppression,

## 2 Introduction

Stricter environmental regulations, new process conditions due to increased production rates or use of other fuels and raw materials place higher performance requirements to ESPs. This can be achieved conventionally by increasing the SCA (Specific Collecting Area), improving electrode configurations, adjusting field separation, or optimizing gas/particulate distribution. Furthermore, considerable performance improvements can be achieved by upgrading high voltage power supplies and controls, even on significantly lower cost. The development of SMPS (Switched Mode Power Supplies) was a milestone for improved ESP efficiency. Today, SMPS are increasingly used in nearly all types of ESP applications as there are additional advantages in the operation compared to the conventional thyristor controlled power supplies.

Ensuring conformity to emission regulations often requires the modernization of existing ESP systems. SMPS provide the opportunity

for improved ESP collecting efficiency to achieve the required emission limit without the requirement for a cost intensive mechanical upgrade.

## 3 More than 20 Years of SMPS Development

Siemens is looking back for more than 20 years of experience in the development and application of SMPS for ESPs. One of the key drivers was the availability of suitable power electronic devices. The main goals for the development of the first SMPS, which was conducted in cooperation with Lurgi AG in the 80s, were:

- a flat, ripple free DC high voltage to increase the corona power compared to the conventional thyristor controlled HV power supplies (see Fig. 3-1).
- minimum 130kW power rating at 100kV DC output
- a very fast flash-over detection

- immediate interruption of the power supply after detection of a flash-over
- fast voltage recovery after flash-over processing

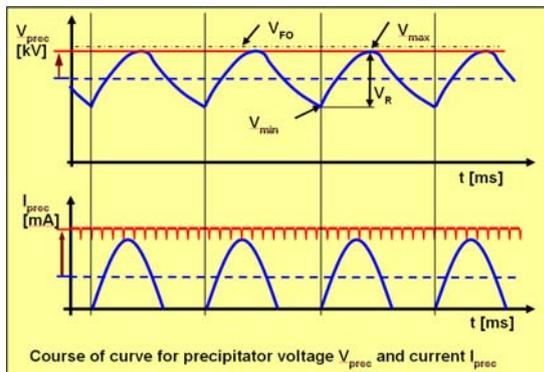


Fig. 3-1: Secondary voltage/current wave forms VARIOVOLT (red) / thyristor controlled T/R set (blue)

The solution was a hard switching DC voltage link and current link inverter with bipolar transistors as power semiconductors and with an inverter switching frequency of 1kHz ready for use in 1989. An appropriate medium frequency TR-set was developed accordingly.

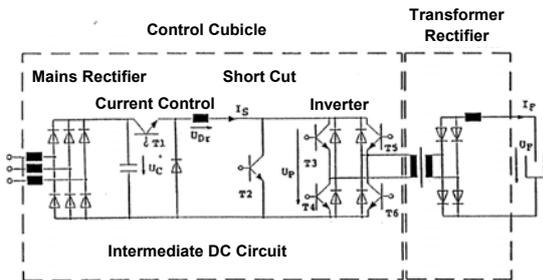


Fig. 3-2: VARIOVOLT basic circuit

The three-phase mains voltage is first rectified to charge the voltage link capacitors. The transistor T1 controls the DC link current and the transistor T2 cuts the power to the inverter T3-T6 immediately when a flash-over is detected. With alternate operation (1kHz) of the transistors T3/T6 and T4/T5 the current  $I_S$  is inverted for the primary supply of the transformer rectifier. After transforming/rectifying the output frequency is 2kHz providing a flat DC voltage.

The SMPS consists of the control cubicle to be installed at the switch room and a separate hermetically sealed transformer rectifier set, suitable for heavy ambient conditions, to be installed typical on the ESP roof. The first SMPS was rated for 135KW with a transformer rectifier output of maximum 110kV/1200mA or 90kV/1500mA. For test installations and for an

easier transportation the control cubicle was divided into 2 small cubicles (control part and power semiconductor part).



Fig. 3-1: VARIOVOLT control cubicle and HV transformer rectifier (1989)

In 1992 a new generation of power semiconductors, the “Insulated Gate Bipolar Transistor” (IGBT) became industrially available. IGBTs offer great advantages compared to standard bipolar transistors in terms of switching properties and robustness.

Thus, the second generation of SMPS (PIC410F) based on IGBTs and a new microcomputer controller could be developed. The switching frequency was chosen at 10 kHz whilst the output current inverting frequency was set to 500Hz, which resulted in significantly smaller power electronics devices and reduced size of the inverter. The SMPS could be rated up to 200KW with transformer rectifier maximum output of 110kV/1800mA or 90kV/2250mA.

The SMPS were designed for 3 phase AC mains input voltage of 380-500V, which made it a symmetrical load on the grid. Parts of the control had been realised using Fuzzy Logic for enhanced control and optimization of the DC operation as well as the intermittent pulsing operation. Due to the fast switching properties and the low transformer inductivity, significantly shorter pulses could be provide compared to conventional power supplies. Beside the operation with the special 500Hz transformer rectifier an existing 50Hz/60Hz transformer rectifier could be operated by the inverter, just by software adaption of the control system.

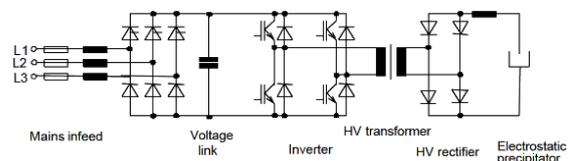


Fig. 3-2: PIC410F basic circuit



Fig. 3-3: PIC410F control cubicle and HV transformer rectifier (1992)



Fig. 3-5: SIPREC I control cubicle and HV transformer rectifier (2011)

In 2006 the third generation of SMPS (PIC420F) with IGBTs as power semiconductors was ready for use. The main difference to the previous version was the use of integrated IGBT power modules for a more compact design of the control cubicle and a power rating up to 275kW. The limitation of the secondary voltage and secondary current rating is based on the design of the transformer rectifier set. For modern ESPs with increasing electrode distances transformer rectifier sets are required with rated secondary voltage above 110kV. The transformer design which has been developed allows increasing output voltage in a rather uncomplicated way.



Fig. 3-4: PIC420F control cubicle and HV transformer rectifier (2006)

The fourth generation of SMPS (SIPREC I) is in the process of development expected to be available end of 2011. The design of the new SMPS is based on the fast switching integrated IGBT modules and includes the latest microcomputer controller technology. In extension the design for the 3AC 690V main input voltage is in process.

## 4 Pre-Test Procedure

SMPS are generally a cost effective solution for increased ESP collecting efficiency. Unfortunately, the potential for this improvement is very difficult to be calculated, due to the high number of process parameters, inhomogenities and unknown geometrical misalignments. Therefore, it's recommended to check some conditions experimentally. A possible procedure will be given below.

At the beginning the measured ESP collecting efficiency is being compared with calculated values based on given process conditions and ESP design parameters. Next, with a plausibility check the electrical measured values for all fields are to be proven, according to the position of the field and the design of the electrode system (type, gas passage, collecting area).

In case of non contradiction, the next step is a simple pre-test with the existing HV power supplies and particulate monitoring system installed. With continuous ESP operating conditions the T/R set output power is to be gradually reduced until significant increase of the opacity value is observed or when ca. 30% of the output power is reduced. Then, the controller is to be set back to normal operation before continuing with the next field.

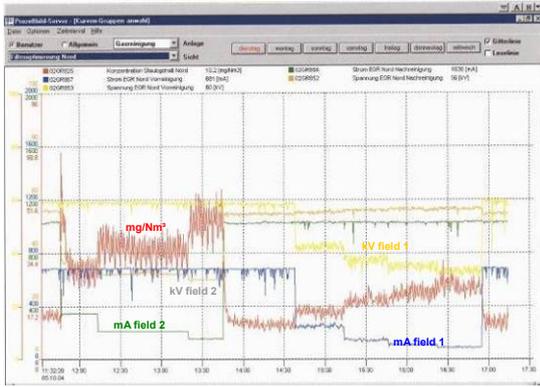


Fig. 4-1: Example for pre-test with existing T/R sets

In addition to the average value of the secondary voltage the peak and minimum voltage value is to be recorded for each measuring point. With the measured values when extrapolating the curve for the average voltage value to the flash-over limit, the estimated secondary current value for the supply with the inverter HV supply can be determined.

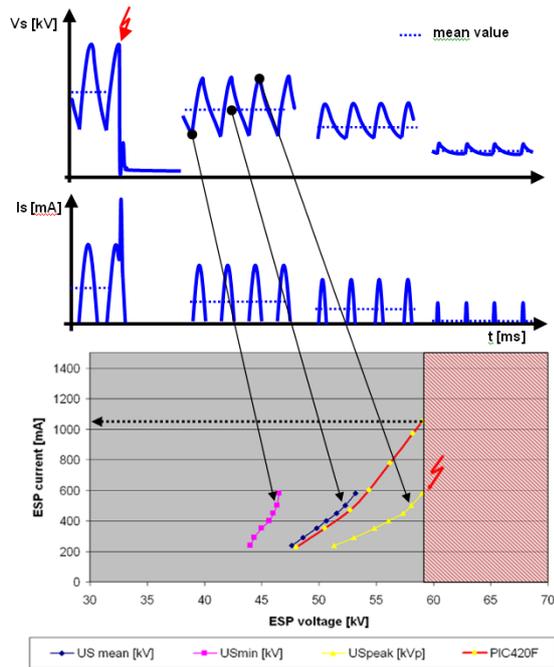


Fig. 4-2: Example IV-curve for estimation of the inverter voltage/current operating point

The estimated operating point for the supply with SMPS than is defined when extrapolating the curve found for the relationship between corona power and emission value.

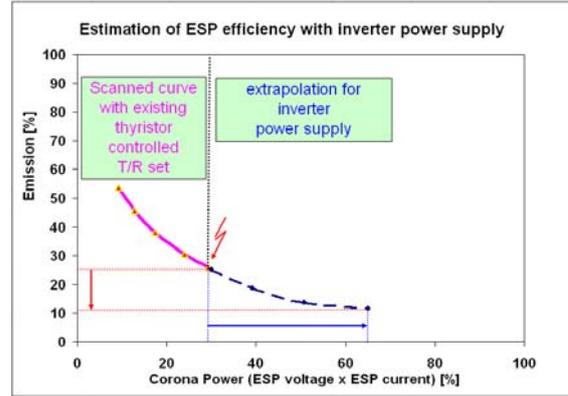


Fig. 4-3: Example for estimation of operating point for the inverter HV power supply

The highest potential for improved ESP collecting efficiency with SMPS is typically (but not solely) found for the gas inlet fields because:

- The influence of the corona suppression due to the high particulate concentration is reduced by the increased corona power with SMPS.
- Increased particle charging/collection in the beginning of the deposition process
- The operation of the gas inlet fields due to the turbulences caused by the high particulate concentration is typically characterized with a high number of flash-over. SMPS improve the average corona power during flash-over processing due to fast voltage recovery and limited space charge generation.

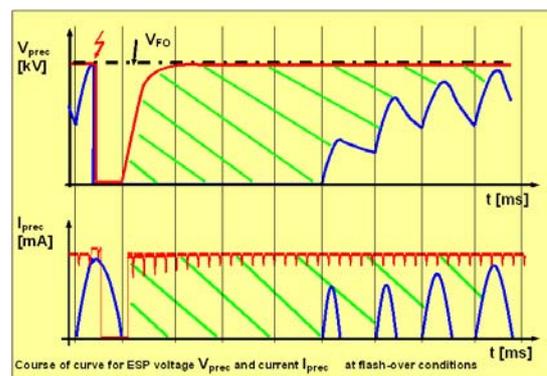


Fig. 4-4: Comparison flash-over processing SMPS/thyristor controlled T/R set

- Decreased particulate concentration after the first fields improves the particulate collecting process for the following fields

Typically, the pre-test is therefore carried out mainly for the gas inlet fields. For very large ESPs with more than 2 parallel fields and e.g. 40 T/R sets influencing only one opacity meter, the pre-test may be carried out with e.g. 2 T/R sets simultaneously.

This test can be also used for comparison the individual influences of parallel fields. Clearly deviation between parallel fields can be an indication for unequal gas/particulate distribution or presence of mechanical faults.

Depending on the estimated improvement for the gas inlet fields the potential for SMPS may also be proven in addition for the remaining zones/fields by the same method particularly for the last zone.

The test method may be insufficient for very discontinuous process conditions typical for the steel converter process or quick process changes. In this case only a test installation can prove the potential for SMPS.

## 5 Test Installation

With positive results of the pre-test, typically a test installation is carried out to demonstrate the advantage of the SMPS for real process conditions. The number of required SMPS depends on the ESP configuration and the availability of the particulate monitoring systems.

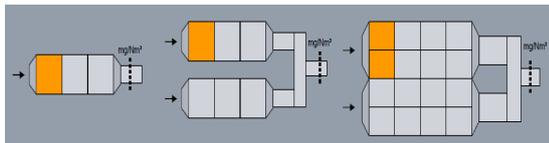


Fig. 5-1: Example for SMPS test installation for different ESP configurations

With estimated operating point for the SMPS by the pre-test the required power rating of the SMPS test equipment is defined. When the power rating of the existing 50Hz/60Hz T/R set is sufficient, the T/R set may be reused in conjunction with a SMPS control cubicle. There is of course a small disadvantage resulting from the higher stray inductance of the standard 50Hz/60 Hz T/R set compared to the 500 Hz type, which results in a higher current turn off time after a flash-over has been detected. But a fairly flat DC voltage can be applied even with the standard TR set to gain a significant performance improvement in many installations.

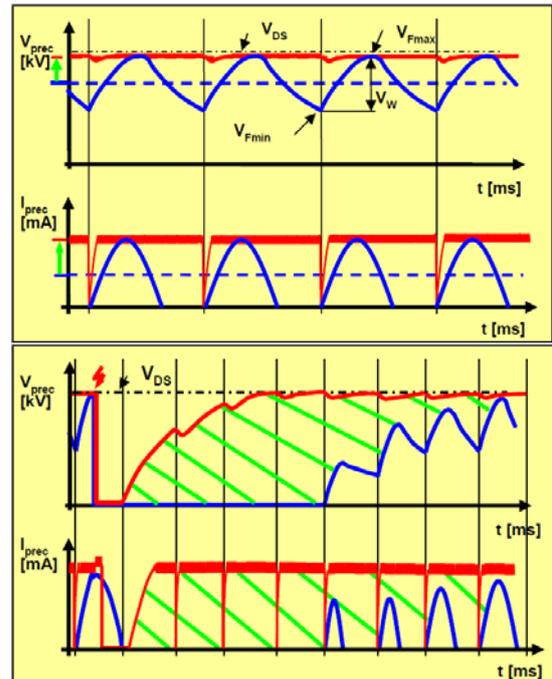


Fig. 5-2: ESP voltage and current wave forms for thyristor (blue) and SMPS (red) power supply

Depending on the local arrangement single or multiple SMPS control cubicles and T/R sets or a container based HV power system (SIPREC M) are to be installed temporary.



Fig. 5-3: SMPS test installation with single T/R set or SIPREC M container solution

After commissioning of the SMPS test equipment it typical takes some time until the

collecting electrode particulate layer has changed to a compact structure. With the integrated Fuzzy Logic functions the operation of the SMPS is optimized for maximum corona power or maximum ESP voltage to achieve the lowest emissions. With the Fuzzy Logic based control the system stability regarding space charge and flash-over rate could be increased significantly. Thus, continuous operation on higher corona power became possible.

With the increased quantity of collected particulates and changed structure of the dust layer the rapping interval times may need to be adjusted. Therefore the SMPS control unit has been equipped with output signals for controlling the collecting electrode rappers.

Optimization of the settings for SMPS operation and collecting electrode rapping has to be proven for different plant operating conditions and steady ESP operation has to be reached. Therefore, the SIPREC ODS PC program has been developed to enable access for remote monitoring and control. Beside the SMPS operation/visualization SIPREC ODS provides the data archiving, trending, optimization functions and diagnostic tools (e.g. oscilloscope functions, IV curve scanning and others).

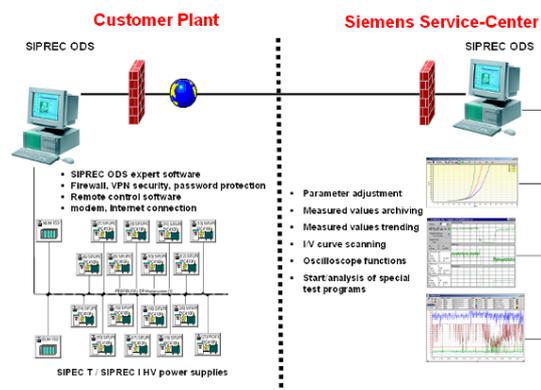


Fig. 5-4: SIPREC ODS remote control

In addition to the measured values of the SMPS, process signals as the stack emission signal, process load, ESP gas inlet temperature and others are to be recorded.

Depending on the process, several load conditions may be investigated, (e.g. different fuel/raw material, part/full load, change over conditions etc.).

A typical test period is 1-2 month. Finally, a test report will be generated to present the

results with a recommendation for the final SMPS installation.

## 6 Experimental Results

SMPS has been successfully tested for many ESP applications as:

- Coal fired power plants (lignite and hard coal)
- Waste incineration plants
- Residue incineration plants
- Refinery power plants
- Cement plants - kiln, mill, bypass
- Paper - recovery boiler
- Steel – converter, sinter plants
- Glass plants - furnace
- Chemical plants - sulfur acid collection

The most success was found, when SMPS were installed at the gas inlet fields, where the corona suppression based on the space charge was high, while the ESP voltage was limited due to the presence of flash-over. SMPS have been tested successfully, too, for ESPs with corona suppression problems based on very fine grain particulates as present with e.g. glass furnace ESPs.

In some cases the clean gas particulate concentration could be also further reduced, when SMPS were installed at the ESP outlet fields additionally.

Small ESPs with 2 or 3 fields may require 2 or even 3 SMPS depending on the gap between existing and required clean gas particulate concentration. The quantity of improvement varies and can reach more than 50% depending on the parameters described above

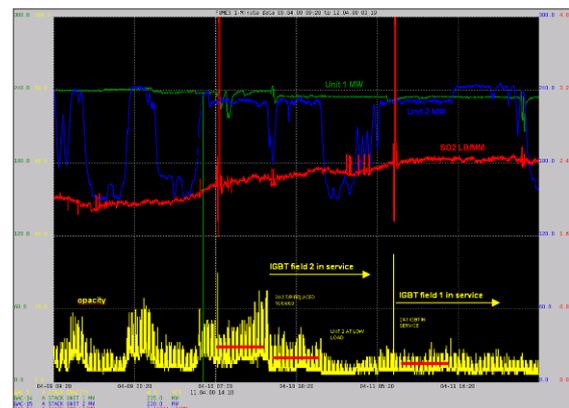


Fig. 6-1: Example increased efficiency - ESP for exhaust gases of a hard coal fired boiler unit

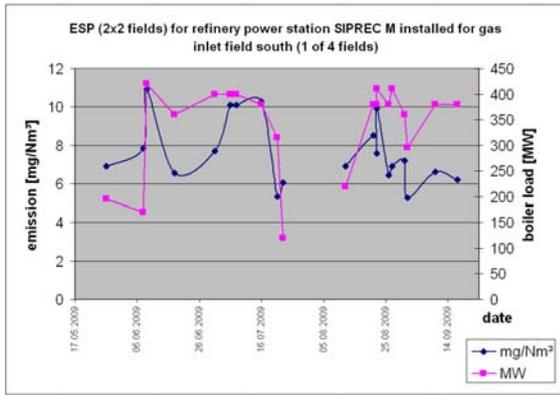
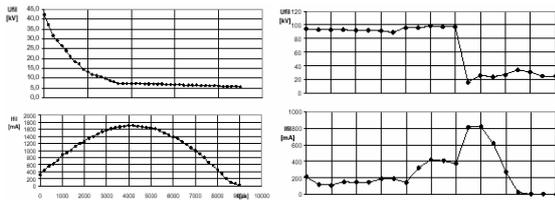


Fig. 6-2: Example increased efficiency - ESP for exhaust gases of a refinery boiler unit

For wet ESPs with typical high ESP voltage ripple when supplied with thyristor controlled T/R sets, the corona power in many cases can be increased by a factor of 2-3 with remarkable improvement of the collecting efficiency. For wet ESPs with plastic collecting electrodes (e.g. PPs) there is an additional advantage of the SMPS gained by the accurate and fast current limitation in case if an arc.



	SIPREC T	SIPREC I
$W_{DS}$	101Ws	5,7 Ws
$W_{CAP}$	31,5Ws	31,5Ws
$W_{total}$ (Sum)	132,5 Ws	37,2 Ws

Fig. 6-3: Short circuit power during ESP discharges: Comparison between thyristor controlled power supply and SMPS

Emission peaks as a result of quick process changes (change of gas/particulate characteristic) can be reduced successfully with SMPS. An example is e.g. ESP for cement kiln/mill when switching between combined and direct operation.

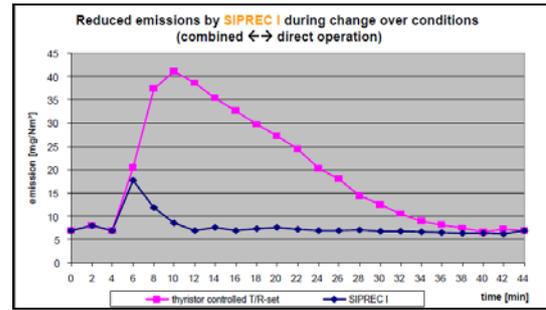


Fig. 6-4: Comparison thyristor controlled power supply and SMPS during change over conditions

SMPS was also tested for a small pilot ESP with a very large electrode distance. In combination with a 50Hz transformer rectifier rated for 300kVp the SMPS reached first time 240kV operating voltage.

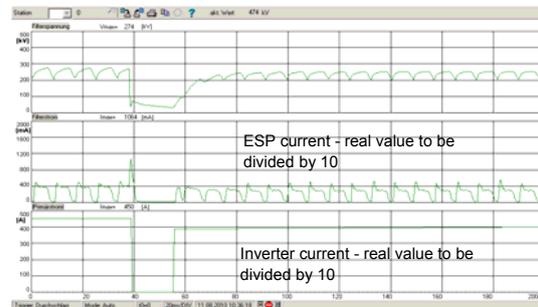


Fig. 6-5: SMPS with 50Hz transformer rectifier

## 7 Performance Increase and Limitation

If the pre-test have not shown any clear tendency for improved collecting efficiency with increased corona power, possible reasons can be:

- ESP mechanical faults
- inadequate gas/particulate distribution
- gas velocity is to high
- retention time is to low
- unfavourable operating conditions

To check for mechanical faults the ESP must be inspected, which is recommended anyway prior to each SMPS test or final installation. In many cases faults were found limiting the potential for improved ESP collecting efficiency. Examples are show below.

Electrode misalignment may cause high electrical field strength at positions with low electrode distances limiting the maximum possible ESP voltage due to the reduced breakdown voltage. With SMPS the corona power is being increased particularly during flash-over processing but this may not be sufficient enough when the increase in corona power is only focused at the positions for low electrode distance.



Fig. 7-1: Discharge frame misalignment with local flash-over marks

Missing or wrong mounted deflector plates of the first/last collecting electrode of each field cause gas bypassing of the electrical field which is then unaffected by the increased corona power supplied by the SMPS. The same situation is given for underflow of the electrode system due to missing baffle plates in front of the fields and in between the fields to the hopper walls.

Non effective cleaning of the gas distribution wall with partly clogging of the some areas impacts negatively the optimum gas/particulate distribution of the complete ESP inlet area. Further problems result from missing or wrong designed gas guiding plates at the row gas income duct. Due to very high gas velocity and particulate concentration in that area, the space charge and low particulate retention time limits the achievable performance improvements even with the usage of SMPS.

Non effective cleaning of the discharge electrodes causes large non uniform particulate layers around the discharge electrodes which lead to suppression of the electrical field strength. The increase in voltage/current by the SMPS is than primary

effective for these areas where the discharge electrodes are sufficiently cleaned.



Fig. 7-2: Figure not cleaned discharge electrode

Insufficient cleaning of the collecting electrode increases the particulate layer thickness, causing decreased flash-over limit, increased particle re-entrainment and depending on the particulate resistivity increases back corona conditions.

When the ESP is operated with under-pressure, false air income at the row gas duct or ESP casing causes unmixed partial cold gas streams. When entering the electrical field the electrical behavior is changed to lower breakdown voltage and in addition corrosion is supported. False air income at the dust removal system or hopper area results in already collected particulates to reenter to the gas stream.

The dust removal system should be checked to handle the increased amount of particulates collected so this is not limiting the increased collecting efficiency.

When the flash-over limit is only slightly higher than the corona onset voltage, the current increase by SMPS is very limited.

With the presence of Back Corona due to high resistive particulates typical the best collecting efficiency is reached with intermittent operation (pulsing). The advantage of the SMPS for intermittent operation is the independent adjustment of pulse width and pulse current to achieve a higher ESP peak voltage with short pulse duration. This requires depending on the operating conditions a very high pulse current (e.g. 3Amp).

## 8 Energy consumption and Energy Savings

The power consumption of large electrostatic precipitators can be in the range of megawatts. To generate this electrical power, additional fuel is needed, causing additional emissions of CO<sub>2</sub> and other environmental pollution. The aim is therefore to ensure maximum ESP collecting efficiency with lowest T/R set power consumption.

In general, based on the SMPS technology the reactive power consumption is remarkable lower compared to the thyristor controlled power supplies.

In addition it has been found that increasing the power in the first fields by SMPS often results in a much lower power demand in the following fields, particularly, when potential for power savings is given during e.g. low load conditions; hence the total electrical power consumption of an ESP can be reduced.

The trend chart shown below presents the operating values for an ESP installed on a hard coal power station. The ESP consists of 4 bus sections with 5 fields in series (20 fields in total). Before the final installation the energy consumption of all bus sections was compared after a SMPS and new thyristor controller where installed temporarily for one bus section. The active power consumption with energy minimization was about 240kW for the bus sections supplied by thyristor controlled power supplies and about 210kW for the bus section with the SMPS installed on the first field.

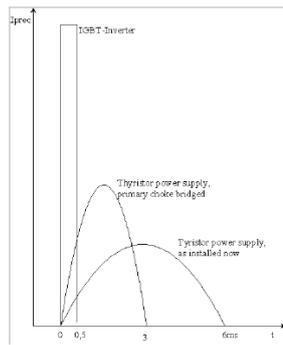


Fig. 7-3: Comparison of pulse currents SMPS versus thyristor controlled T/R set

Additionally, the wave form of the pulse can be individual shaped to match the back corona conditions.

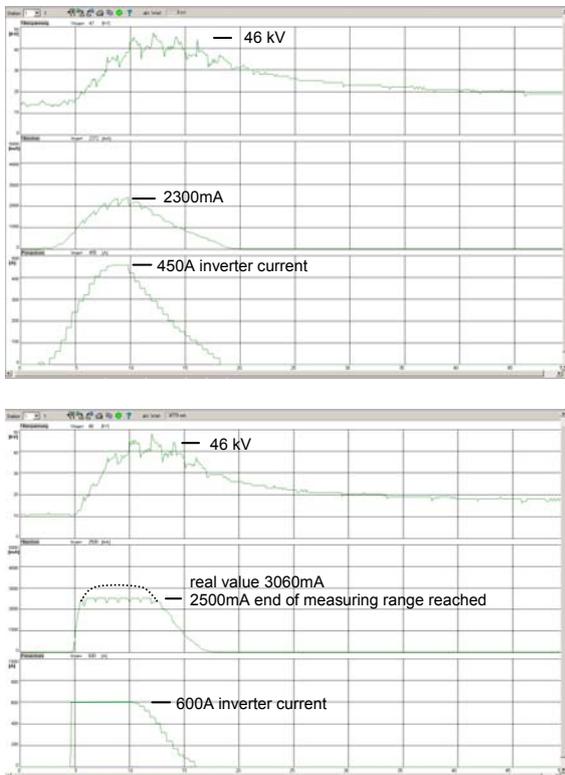


Fig. 7-4: Example for different SMPS pulse current wave forms

In case of electrical flash-over occurring during operation, the pulse waveform can be optimized to transfer maximum possible charge during the pulse interval due to the fast switching properties of the SMPS.

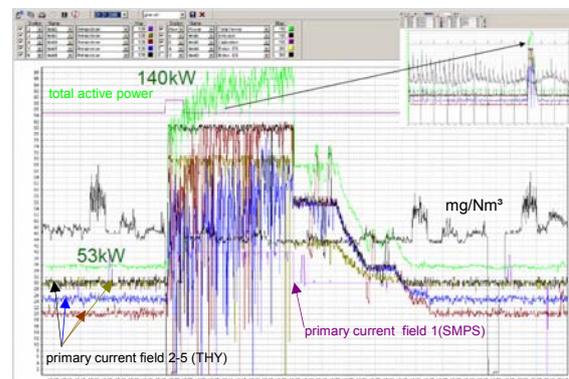


Fig. 8-1: Example for energy savings with SMPS installed for the first field

## 9 Permanent Installation

Beside the increased collecting efficiency SMPS provides advantages on the grid side, as a high power factor, balanced three-phase load and lower harmonic currents compared to the thyristor controlled power supplies. Indications for SMPS installations on new ESPs are:

- extremely low dust emission requirements (<10mg/Nm<sup>3</sup>)
- on high raw gas particulate concentrations
- for collection of very fine grid particulates
- wet ESP applications.

In case of modernization of existing ESPs the collecting efficiency, SMPS are permanently installed after a successful test installation has demonstrated the required performance increase. In some cases the test equipment remained permanently.

Typically, mixed installations of SMPS and thyristor controlled power supplies have been carried out in the past. With the modernization work the thyristor controllers were upgraded to the newest technology in addition to the installation of the SMPS. Then, all controllers can be networked to the DCS and centrally optimized by e.g. SIPREC ODS for highest ESP collecting efficiency and power savings.

## 10 Literature

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