# Results from ESP-upgrades, including control systems

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## Abstract:

Meeting new demands on particulate emissions from power plants and industrial processes in a cost effective way is important for the industry. Upgrading ESPs to higher performance levels include different measures. This paper presents result from such upgrades where the dominant part is the upgrade of power-supplies and control system.

Upgrading of the power supplies and control system so that the collection efficiency is optimized has, in many cases, proven to be a cost effective measure to reach new levels of emissions, stipulated by more stringent legislations. However, a successful ESP upgrade is dependent on more than just power supply and control system upgrades, various upgrade options are discussed in the present paper.

## 1 Introduction

It is the objective of this paper to present results from ESP performance improvement projects where the dominant part of the upgrade relates to the energization and control system of the ESP. Specifically are results from upgrades including high frequency power supplies, [1], [2], studied,

The paper presents results from several performance improvement projects at different plants. Section 1 provides an introduction to the subject including; an overview of business drivers, a brief description of the basic principles of electrostatic precipitation, an introduction to power supplies, a discussion on rapper system control and common measures related to ESP upgrades. Section 2 provides six case studies from completed ESP-upgrade projects, where plant A is described in detail while plant B-E are described on higher level. Section 3 presents a discussion of the results and Section 4 provides the conclusions from the presented work.

### *Drivers for ESP upgrades*

The main purpose of the ESPs at a plant is to bring the particulate stack outlet concentration below the permitted limits. Typical drivers for ESP upgrades are:

- Performance degradation
- More stringent legislation
- Production increase
- Fuel change

Performance degradation, by corrosion and erosion will the collection efficiency of the ESP degrade by time. This is often due to corroded electrodes, screens and baffles. The electrical erosion caused by spark-overs as well as the impulses from rapping may, by time have a negative effect on the efficiency.

More stringent legislation brings the permitted particulate emission concentrations to lower and lower levels. This calls for higher particulate collecting efficiencies compared to the original design requirements.

Higher production volumes will increase the amount of fuel as well as the gas flow. For an existing ESP it means higher dust load and gas velocity, both factors will increase the particulate outlet and may require an ESP upgrade.

New fuels with different chemical compositions may change the ESP operational conditions in such a way that the emission limits are no longer possible to meet without a performance improvement of the ESP.

## Electrostatic precipitation

A general description of the fundamental operation of an ESP is presented in Fig. 1.1. The flue gas is made to pass between two electrodes, the discharge electrode (DE) and the collecting electrode (CE). A high DC voltage is applied to the electrodes, typically so that the CE is connected to ground and the DE to a negative potential (20-150 kV). The high electrical field close to the DE initiates a corona discharge, i.e. negative charges are emitted from the DE into the gas flow.

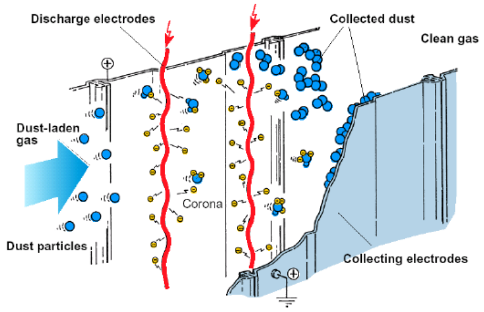


Fig. 1.1 Electrostatic dust precipitation

The negative charges will drift towards the positive electrode, CE. Some of the charges will stick to particles and make these charged and to drift in a similar way towards the CE. The collected dust is dislodged by means of mechanical rapping or by spraying water.

The electrical characteristic of an ESP bus-section is given by the energy storage in the electrical field, capacitance of the bus-section, and the corona discharge characteristic, VI-curve. Fig. 1.2 indicates the corona discharge characteristic, i.e. the VI-curve [5], [6], [7]. From the diagram the non-linear characteristic is clearly indicated. Below a threshold voltage, $U_{onset}$, no corona current is present. However, above $U_{onset}$ the current will increase with an increasing voltage, steeper at higher voltages. The operation is limited by the spark-over voltage, $U_{spark}$.

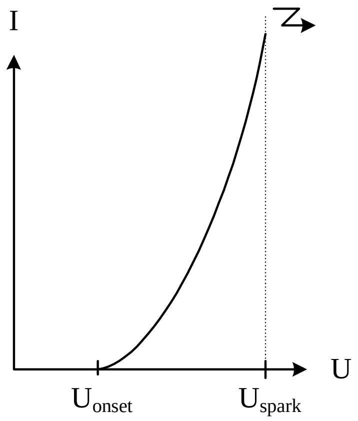
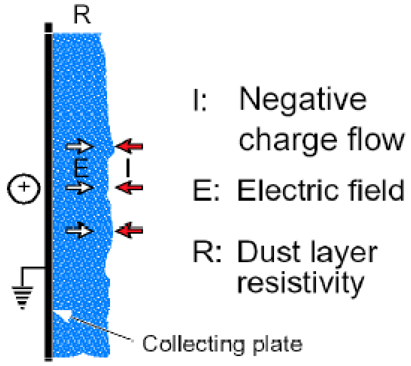
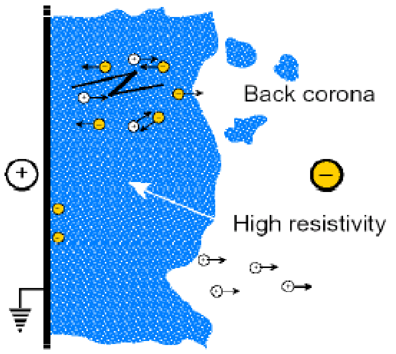


Fig. 1.2: Electrical characteristic, VI-curve

From Fig. 1.1 is also observed that the corona charges have to pass through the dust-layer in order to reach the CE. Fig. 1.3 shows the dust-layer in a more detailed view.



(a)



(b)

Fig. 1.3 Dust layer; (a) General, (b) High resistivity dust.

Fig. 1.3(a) shows the general case where the flow of negative charges form an electrical field in the dust-layer. The field strength, *E*, is given by the current density, *J*, and the dust-layer resistivity, *R*, as

$$E = J \cdot R \, . \tag{1}$$

In a situation where the dust resistivity, Fig. 1.3(b), is high, back-corona, [5], [6], [7], may occur, i.e. the field strength in the dust-layer is high enough to cause local spark-over, which injects positive charges into the gas stream. The positive charges recombine with the negative charge from the DE. Consequently, the collecting efficiency is reduced as the power consumption is increased. Fig. 1.4 indicates the collecting efficiency as a function of input power for back-corona and non-back-corona conditions, respectively. The diagram shows that in the case of back-corona the emission will start to increase if the power is increased above a certain level. In the case of non-back-corona operation the emission is decreasing for an increased power input.

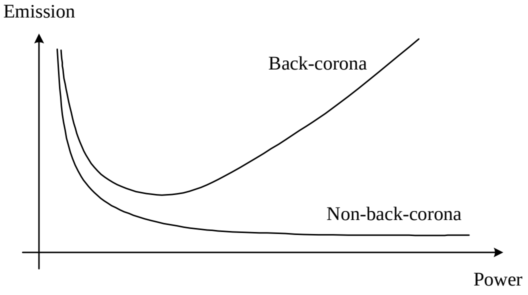


Fig. 1.4: Dust emission vs input power

In order to reduce the negative effects from back-corona, the corona current has to be reduced. This is preferably achieved by pulsed mode operation [3], [4], [8], [9]. Fig. 1.5 shows the current to the ESP bus-section in pulsed mode operation, i.e. intermittent energization.

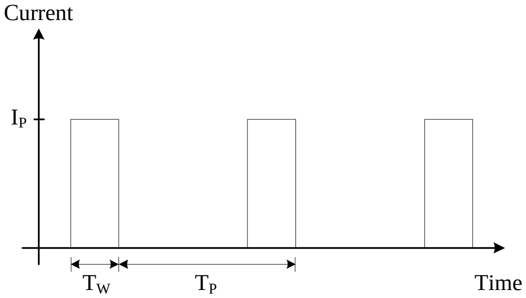


Fig. 1.5 Idealized current waveform

Since the average current is kept at a low level in pulse mode operation the back corona is limited. However, the high peaks of the current ensure an even current distribution over the DE, which improves the collecting efficiency.

## *Energization, power supplies*

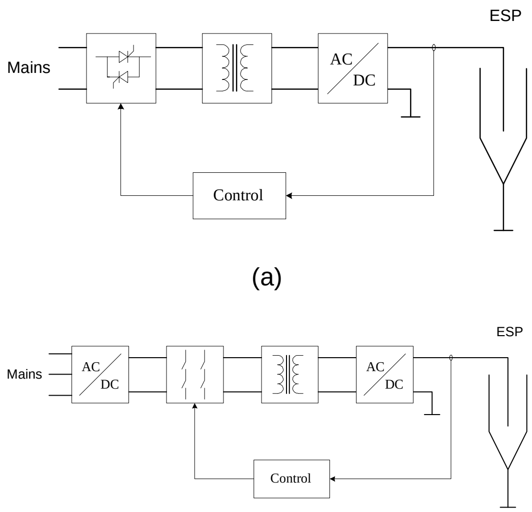
The energization systems, power supplies considered in this paper are; line frequency power supplies and high frequency power supplies, HFPS. The related block diagrams are shown in Fig. 1.6 (a), (b), respectively.

Other types of power supplies, than the above mentioned, like three-phase line-frequency systems and systems which are restricted to pulsed energization are not considered in this paper since their penetration of the market is limited.

High-frequency power supplies were originally introduced on the ESP market in 1993 [1]. An evaluation of the experiences gained during the first decade of operation was presented in [2].

Fig. 1.6 (a) shows the block diagram of aline-frequency power supply. A phase-to-phase voltage from the mains is supplied to a pair of anti-paralleled thyristors, which are connected in the primary circuit of a high-voltage transformer. The secondary winding of the transformer is connected to a diode rectifier. The DC-output of the rectifier is connected to the DE of an ESP bus-section. The high voltage transformer and the output rectifier are commonly housed in an oil-filled vessel and is referred to as a T/R-set. The voltage and current of the ESP are sensed by a controller, which controls the conduction angle of the thyristors. This topology of the power supply was established in the 70s when the power thyristor was introduced.

More recently the high frequency power supply (HFPS) has been introduced, Fig. 1.6 (b). The first commercial installations were made 1993 and the original publication [1] was published in 1995.  In 2004 at the ICESPIX was [2] published in order to present operational experiences from this novel technology.
The major difference compared to the mains frequency power supply is the much higher operational frequency, 25-50 kHz vs 50/60 Hz. The HFPS is fed from the three phase mains. The input voltage is rectified and supplied to a transistor-bridge configuration. The transistors are turned on and off in a sequence so that the required high frequency voltage is applied to the transformer primary. The secondary of the transformer is rectified and connected to the ESP. For more technical details on HFPS technology, see [10], [11].



(a)

(b)

Fig. 1.6: Block diagrams of ESP power supplies; (a) Line frequency, (b) High frequency

Fig. 1.7 compares the ESP voltages obtained when energized from a line frequency power supply and a high frequency power supply, respectively, [1].

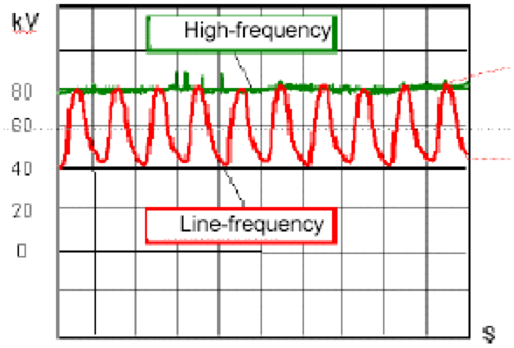


Fig. 1.7: Voltage ripple; line frequency power supply and high-frequency power supply

As a consequence of the almost ripple free voltage, in the case of HFPS energization, more current can be supplied to the ESP. The higher corona current and the increased average voltage will improve the collecting efficiency, in the case of non-back-corona conditions, Fig. 1.4. In the case of back-corona conditions the power supply is operated in pulsed mode, intermittent energization, Fig. 1.5, [8]. In this mode of operation the resulting voltage includes a high ripple content. This to ensure an efficient current distribution on along the DE while maintaining a low average current in order to control the amount of back corona.

## *Rapper Control systems*

Cleaning of the CE plates are most often performed in a timed predefined sequence, where the CE plates are impacted, rapped, in order to dislodge the collected dust and make it enter into the dust transport system. Due to the local disturbance to the dust layer, when rapping, the particulate emission will increase, temporarily, as a result of the rapping event. In order to minimize particulate emission it is very important to optimize the rapping procedure, [12]. This is mainly done in two ways:

> -Optimize the sequence of rapping, i.e. the timing and the pattern of rapping are optimized.

-Optimize the energization in relation to the rapping sequence, i.e. to control the holding forces in the dust-layer in order to minimize emissions.

The optimization, tuning, of the rapping procedure is often a very time consuming effort. This, since the build-up and settling of the dust-layer may take long time, specifically in the case of high-resistivity dusts and back-corona conditions. Moreover, under such conditions an efficient rapping procedure may even lower the effective resistivity of the dust layer.

Consequently, from different aspects a proper tuning of the rapping procedure may have a significant impact on the particulate emission levels and is most often required in order to meet the lowest possible emission levels.

### *ESP upgrades measures*

In order to upgrade existing ESPs to meet more stringent regulations or to keep existing limits while changing fuel or increasing output power different measure can be used.

Find listed below typical measures for ESP upgrades:

- *Mechanical upgrades*
  *Field extension*
  *Electrodes, DE, to more efficient ones.*
  *Repair (corrosion, erosion, rapping)*
  *Perfection of alignment and baffling*
  *Rapping system*
  *Gas flow distribution*
- *Electrical upgrades*
  *Control system*
  *H-V generation (i.e. HFPS)*
- *Chemical*
  *Fuel additives*
  *Gas-stream sorbent injection*
- *Tuning*
  *Maximizing power input (spark handling)*
  *H-V Intermittency set up*
  *Rapper sequence optimization*

# 2 Case studies

In order to evaluate the efficiency of ESP upgrades where power-supplies and control system are the dominant parts five different upgrade projects, plant A to E, have been analyzed. All studied plants are coal fired utility boilers. Plant A is located in Europe while plants B to E are located in US.

It should be noted that in the description of the studied cases the Alstom product brands are used for the specific components:

SIR – High frequency power supply

EPIC – T/R set controller

EPOQ- Optimization algorithm for pulse mode operation

ERIC – Gravity Impact Rapper Controller

PROMO – Process monitoring and data logging system, remote control

## 2.1 Plant A

Plant A is a lignite fired boiler located in Europe. The plant is using coal from a local seam. There are four units each designed to produce 305 MW each. However, the energy content of the coal is occasionally limiting the output power to lower values. For unit 1 and 2 the existing ESPs emit too much dust to meet new legislations. The owner wanted to make a test installation in one out of the 4 ESP casings to verify if modern technology could reduce the emission by 20 % or more.

Fig. 2.1 Plant A, Lignite fired utility plant

Fly-ash from firing Lignite is often considered easy to catch with ESPs. In this case the situation is reversed mainly due to two reasons:

1. The high content of free (10-40%) Calcium that consumes all $SO_x$ from the flue gas rendering the fly-ash high resistive.
2. The particle size distribution with a high fraction of fines resulting in corona quenching and risk of ash build-up in exit fields.

These two properties challenge the ESP fly-ash collection substantially in terms of significant back-corona and difficulties in reducing the amount of ash on the collector electrodes by rapping.

The upgrade at unit 1 targeted at reducing the load on the environment by upgrading a 20 year old ESP constituting 2 casings each with three passes and 4 fields. The ESPs were in acceptable mechanical condition for their age but with multi-peak electrodes which is not ideal for back-corona situations (less uniform current distribution than weighted wire or spiral electrodes). The gas distribution status was unclear regarding in the ESP cross-sections. Furthermore the tumbling rapper motors were designed for continuous rapping meaning approximately 0,25 rpm. Alstom research has proven that 1 rpm motors sequenced to operate without coinciding events result in significantly lower particulate emission.

### 2.1.1 Discussions:

*Entry field corona quenching*

The high ESP inlet loading (>30 g/Nm$^3$) and the high percentage of fines pushed the corona on-set voltage to high levels resulting in low secondary current at spark over voltage.

One counter-measure for this is multi-peak or pipe and spike electrodes, but in this case multi-peak electrodes were already in place.

Another counter-measure is efficient rapping. Hence, it was decided to upgrade all collector rapper motors to 1 rpm knowing that this enabled less coinciding rappers, lower rapping losses and reduced negative impact from PCR.

An important part of improving rapper operation is to control power during rapping, (Power Control Rapping, PCR). This is an area where Alstom has a proven record for both low- and high resistivity fly-ash ESP upgrades by advanced rapping schemes, so a controller upgrade was decided.

A very efficient and well-known way of countering corona quenching is to use High Frequency Power Supplies (HFPS) due to the low voltage ripple, as discussed in Section 1. For ESPs facing back-corona the power-profile through the ESP is of high interest. In the entry fields the back-corona effect is less evident due to the fact that the dust on the collector plates has less average resistivity. (the smaller and higher resistivity particles have a lower migration velocity and hence need more time to travel to the collector plates resulting in more fines and higher resistivity in the exit fields). Another topic is that it may pay off to charge aggressively while accepting some back-corona in the entry fields leaving the collection and back-corona control to the down-stream fields.

At this plant corona quenching was fore-seen so to use an HFPS in the first field was decided. As the suitable Alstom HFPS controller has a very advanced built in rapper control feature, the rapping improvement requirement would be fulfilled. To have backup during PCR, an HFPS was decided also for the second fields. In the two down-stream fields HFPS would have been more efficient due to the more exact pulse control, but the pay-back in terms of higher migration velocity was not high enough to warrant the replacement of the existing T/R sets. The dated in-situ thyristor controllers had to be replaced with modern Alstom controllers for best possibility to counter-act on back-corona and to control rapping efficiently in these fields.

Decided upgrade package:

1. HFPS in the first two fields
2. Modern 50 Hz T/R controllers in the down-stream fields using the existing T/R sets.
3. 1 rpm rapper motors for all collector rappers.

4. Rapper control from the High Voltage controllers regardless of HFPS or 50 Hz.

5. On-site fine tuning of Voltage control and rapping control.

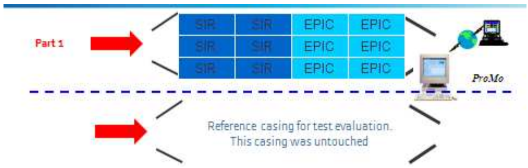
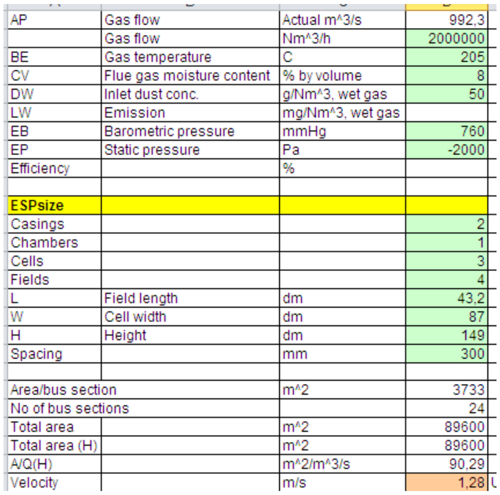


Fig. 2.2. Test layout

Fig. 2.3. Installation of SIR

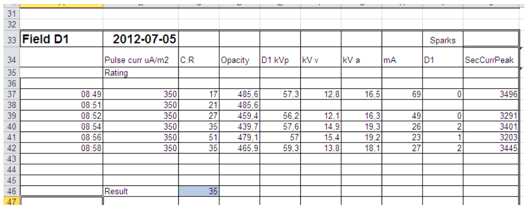
**Table 1. ESP data**



| | | | |
|---|---|---|---|
| AP | Gas flow | Actual m^3/s | 992,3 |
| | Gas flow | Nm^3/h | 2000000 |
| BE | Gas temperature | C | 205 |
| CV | Flue gas moisture content | % by volume | 8 |
| DW | Inlet dust conc. | g/Nm^3, wet gas | 50 |
| LW | Emission | mg/Nm^3, wet gas | |
| EB | Barometric pressure | mmHg | 760 |
| EP | Static pressure | Pa | -2000 |
| Efficiency | | % | |
| | | | |
| ESPsize | | | |
| Casings | | | 2 |
| Chambers | | | 1 |
| Cells | | | 3 |
| Fields | | | 4 |
| L | Field length | dm | 43,2 |
| W | Cell width | dm | 87 |
| H | Height | dm | 149 |
| Spacing | | mm | 300 |
| | | | |
| Area/bus section | | m^2 | 3733 |
| No of bus sections | | | 24 |
| Total area | | m^2 | 89600 |
| Total area (H) | | m^2 | 89600 |
| A/Q(H) | | m^2/m^3/s | 90,29 |
| Velocity | | m/s | 1,28 |

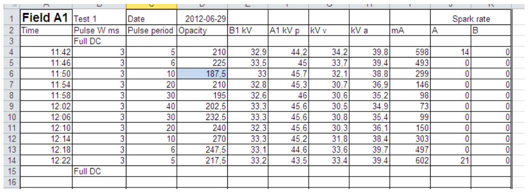
### *Tuning procedure*

A detailed sequence for finding best possible pulsed mode settings was devised and followed.



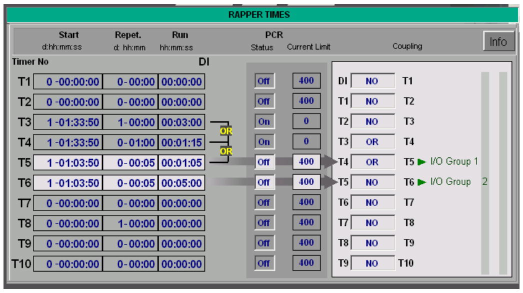
| Field D1 | 2012-07-05 | | | | | | | Sparks | |
|---|---|---|---|---|---|---|---|---|---|
| | Pulse curr uA/m2 | C:R | Opacity | D1 kVp | kV v | kV a | mA | D1 | SecCurrPeak |
| | Rating | | | | | | | | |
| | | | | | | | | | |
| 08:49 | 350 | 17 | 485,6 | 57,3 | 12,8 | 16,5 | 69 | 0 | 3496 |
| 08:51 | 350 | 21 | 485,6 | | | | | | |
| 08:52 | 350 | 27 | 459,4 | 56,2 | 12,1 | 16,3 | 49 | 0 | 3291 |
| 08:54 | 350 | 35 | 439,7 | 57,6 | 14,9 | 19,3 | 26 | 2 | 3401 |
| 08:56 | 350 | 51 | 479,1 | 57 | 15,4 | 19,2 | 23 | 1 | 3203 |
| 08:58 | 350 | 35 | 465,9 | 59,3 | 13,8 | 18,1 | 27 | 2 | 3445 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | Result | 35 | | | | | | | |

Fig. 2.4. Example of 50 Hz controller tuning sequence.



| Field A1 | Test 1 | Date | 2012-06-29 | | | | | | Spark rate | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Pulse W ms | Pulse period | Opacity | B1 kV | A1 kV p | kV v | kV a | mA | A | B |
| | Full DC | | | | | | | | | |
| 11:42 | 3 | 5 | 210 | 32,9 | 44,2 | 34,2 | 39,8 | 598 | 14 | 0 |
| 11:46 | 3 | 6 | 225 | 33,5 | 45 | 33,7 | 39,4 | 493 | 0 | 0 |
| 11:50 | 3 | 10 | 187,5 | 33 | 45,7 | 32,1 | 38,8 | 299 | 0 | 0 |
| 11:54 | 3 | 20 | 210 | 32,8 | 45,3 | 30,7 | 36,9 | 146 | 0 | 0 |
| 11:58 | 3 | 30 | 195 | 32,6 | 46 | 30,6 | 35,2 | 98 | 0 | 0 |
| 12:02 | 3 | 40 | 202,5 | 33,3 | 45,6 | 30,5 | 34,9 | 73 | 0 | 0 |
| 12:06 | 3 | 30 | 232,5 | 33,3 | 45,6 | 30,8 | 35,4 | 99 | 0 | 0 |
| 12:10 | 3 | 20 | 240 | 32,3 | 45,6 | 30,3 | 36,1 | 150 | 0 | 0 |
| 12:14 | 3 | 10 | 270 | 33,3 | 45,2 | 31,8 | 38,4 | 303 | 0 | 0 |
| 12:18 | 3 | 6 | 247,5 | 33,1 | 44,6 | 33,6 | 39,7 | 497 | 0 | 0 |
| 12:22 | 3 | 5 | 217,5 | 33,2 | 43,5 | 33,4 | 39,4 | 602 | 21 | 0 |
| | Full DC | | | | | | | | | |
| | | | | | | | | | | |

Fig. 2.5. Example of HFPS tuning sequence.



| Timer No | Start d:hh:mm:ss | Repet. d: hh:mm | Run hh:mm:ss | PCR Status | Current Limit | Coupling | | |
|---|---|---|---|---|---|---|---|---|
| T1 | 0 -00:00:00 | 0-00:00 | 00:00:00 | Off | 400 | DI | NO | T1 |
| T2 | 0 -00:00:00 | 0-00:00 | 00:00:00 | Off | 400 | T1 | NO | T2 |
| T3 | 1 -01:33:50 | 1-00:00 | 00:03:00 | On | 0 | T2 | NO | T3 |
| T4 | 1 -01:33:50 | 0-01:00 | 00:01:15 | On | 0 | T3 | OR | T4 |
| T5 | 1 -01:03:50 | 0-00:05 | 00:01:05 | Off | 400 | T4 | OR | T5 |
| T6 | 1 -01:03:50 | 0-00:05 | 00:05:00 | Off | 400 | T5 | NO | T6 |
| T7 | 0 -00:00:00 | 0-00:00 | 00:00:00 | Off | 400 | T6 | NO | T7 |
| T8 | 0 -00:00:00 | 1-00:00 | 00:00:00 | Off | 400 | T7 | NO | T8 |
| T9 | 0 -00:00:00 | 0-00:00 | 00:00:00 | Off | 400 | T8 | NO | T9 |
| T10 | 0 -00:00:00 | 0-00:00 | 00:00:00 | Off | 400 | T9 | NO | T10 |

Fig. 2.6. Rapper tuning

Fig. 2.6 shows a fairly simple rapping sequence utilizing 4 timers of which three are connected with Boolean algebra.

### *Verification, measurements*

As the quality of the lignite was difficult to control and was expected to vary during the test campaign it was decided to use one casing after the selected boiler for the upgrade (test ESP) and the other casing, after the same boiler, as a reference (ref. ESP)

The dust emission from each ESP was measured gravimetrically before the upgrade and then again after the up-grade.

A number of measurements were conducted and the valid ones were averaged for a calculation of average improvement after correction.

**Table 2. Test results, [mg/Nm$^3$]**

| ***Test 1*** | ***(prior to upgrade)*** | | |
|---|---|---|---|
| ***No.*** | ***Ref. ESP*** | ***Test ESP*** | ***Relation*** |
| 1 | 177 | 422 | |
| 2 | 119 | 297 | |
| 3 | 110 | 248 | |
| 4 | 188 | 412 | |
| 5 | 191 | 405 | |
| Average | **157** | **357** | 2,3 |
| ***Test 2*** | ***(post upgrade)*** | | |
| 1 | 384 | 710 | |
| 2 | 351 | 619 | |
| 3 | 380 | 573 | |
| 4 | 492 | 651 | |
| 5 | 424 | 556 | |
| Average | **406** | **622** | 1,5 |
| | **Relative reduction** | | **32,6%** |

Table 2 shows test results comparing emission before and after upgrade relative to the reference casing. The relative reduction of 32.6% is encouraging and illuminates the potential in HFPS, ESP control and tuning upgrades.

## 2.2 Plant B

Plant B is located in Michigan, US, and consists of 4 coal fired units, each nominally 800 MW units that were put into service 1971-1974.

The electrostatic precipitators were supplied by Research Cottrell and have the typical weighted wired discharge electrodes, OPZEL collector plates and MIGI rappers. Each precipitator has four (4) chambers in a “piggy back” four square arrangement and each chamber has four cells, three mechanical fields and five electrical fields in series. The installed SCA is 214.

In recent years the plant has transitioned from burning medium sulfur bituminous coal to firing Powder River Basin (PRB) 0.4% sulfur sub bituminous coal. The firing of PRB coal presented a problem to keep the particulate mass emission and opacity within the unit permit requirements.

The precipitators on unit 1 and 2, the older of the units, were retrofitted approximately seven (7) years ago. New wires were installed and internal alignment issues were corrected to improve reliability and the traditional Transformer/ Rectifier (T/R) sets were replaced with the SIR-E high frequency power supplies to enhance performance.

A total of forty eight (48) SIR-E power supplies are now installed on each unit precipitator. The first electrical fields have SIR-Es that energize two (2) adjacent high voltage frames while the high voltage frames in the last electrical field are independently energized by a SIR-E. In 2011 a Promo III data logging system was installed, and as part of the service agreement the SIR- E controls were updated with the latest EPOQ software.

The installation of the SIR units increased the performance of the small precipitators to such a degree that the precipitators now meet both the particulate mass emission and opacity permit compliance limits with the boiler units operating at full load.

## 2.3 Plant C

Plant C is located in Alabama, US, and has 5 coal fired units.

The largest of the boiler is 550mW commissioned in 1976. The boiler unit was fitted with a Walther European design precipitator comprising two independent casings each with two (2) chambers. The precipitator had four (4) fields in series and eight (8) parallel cells and an installed SCA of approximately 326. The internal components consisted of barbed emitters in rigid frames, roll formed collector panels installed with 12” spacing and tumble hammer rapper systems. The power supplies were conventional transformer rectifiers with saturable reactors and analogue controls.

The precipitator design was based on firing 1.5% sulfur bituminous coal. In recent years, however, in order to reduce the $SO_2$ emissions the coal supply to the plant was changed to low sulfur 0.5% Colorado bituminous coal and an SCR for $NO_x$ reduction was added to the unit. Sulfur trioxide flue gas conditioning at a rate of 8-10 ppm was injected to condition the fly ash and compensate for the low sulfur in the coal.

The precipitator over the years suffered from high temperature excursions and the internal components deteriorated to the level that the precipitator was not reliable. In order to maintain the average stack opacity at less than the 20% limit unit load reduction was required on many occasions.

The owner awarded Alstom the contract in 2010 to rebuild the precipitator. The scope was to replace the precipitator internals with current technology components and replace the transformer rectifiers with SIR-E high frequency power supplies.

The internals were rebuilt with Multipeak high emission discharge electrodes and roll formed collector plates with 12” spacing for first field and Spiral discharge electrodes and roll formed collector plates with 15.75” spacing for fields 2, 3 & 4.
Each of the thirty two (32) bus sections were powered with SIR- E’s high frequency power supplies rated at 70kV 800mA. A PROMO III Ethernet based supervisory system was also installed.

The rebuilt precipitator system allowed the injection of $SO_3$ to be discontinued and the performance test particulate emission measurement was less than 0.01 lb/mmBtu with the average stack opacity of 2%.

## 2.4 Plant D

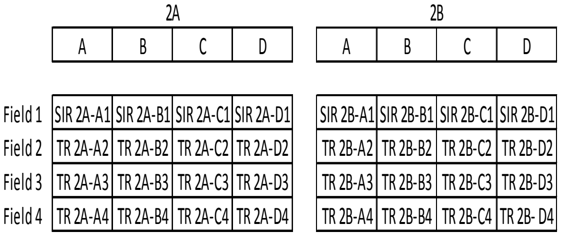
Plant D has two 900 MW units installed in 1967 and 1968. The units are fitted with precipitators as the particulate cleaning device. The precipitators for each unit comprise two independent casings configured in a Chevron arrangement. The precipitators have Four (4) fields in series and an SCA of approximately 208. The internal components are weighted wire discharge electrodes, collector plates arranged with nine (9) inch spacing and electro- magnetic impact hammer rappers, a common design for the time. Each precipitator was powered with Forty (40) transformer-rectifiers each rated at $70kV_{peak}$, 1000mA.

Over the years of service the precipitators were refurbished with in kind replacement components but no major changes.

The fuel burned at the plant is nominally 1% sulfur Eastern US Bituminous coal.

As legislation became more stringent the plant was required to conform with new particulate mass emission limits and a stack opacity limitation of 20%. While this was just achievable when all sections of the precipitator were in service there was little margin of safety to allow for internal problems or failures. Any exceedances of the opacity limit required the boiler load to be reduced until the opacity was below 20%.

In order to reduce the everyday opacity and provide a margin of safety modifications were made to the powering of unit 2 precipitator. The eight (8) conventional transformer - rectifiers on the first field were replaced with eight SIR Type- E 60 kV 1000 mA high frequency power supplies additionally the sixteen (16) analogue controllers on fields 2 & 3 transformer- rectifiers were replaced with latest state of the art EPIC III controllers. The controller for the rappers was also replaced with an ERIC integrated controller.



| | 2A | | | | 2B | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D |
| Field 1 | SIR 2A-A1 | SIR 2A-B1 | SIR 2A-C1 | SIR 2A-D1 | SIR 2B-A1 | SIR 2B-B1 | SIR 2B-C1 | SIR 2B-D1 |
| Field 2 | TR 2A-A2 | TR 2A-B2 | TR 2A-C2 | TR 2A-D2 | TR 2B-A2 | TR 2B-B2 | TR 2B-C2 | TR 2B-D2 |
| Field 3 | TR 2A-A3 | TR 2A-B3 | TR 2A-C3 | TR 2A-D3 | TR 2B-A3 | TR 2B-B3 | TR 2B-C3 | TR 2B-D3 |
| Field 4 | TR 2A-A4 | TR 2A-B4 | TR 2A-C4 | TR 2A-D4 | TR 2B-A4 | TR 2B-B4 | TR 2B-C4 | TR 2B- D4 |

Fig. 2.7 Selection of power supplies for different fields

Prior to the installation of the SIRs and the EPIC III controllers the Unit 2 boiler full load particulate average opacity was 17-18%. Following the installation the boiler full load particulate average opacity was 10-11%. This reduction in opacity corresponds approximately to a 40% reduction in particulate emission.

## 2.5 Plant E

Plant E has four small boilers. The largest and newest of these is Unit 4 rated at 218 MW, commissioned in 1968.

The unit 4 precipitator is a Joy Western unit with weighted wire discharge electrodes, roll formed collector plates and MIGI rappers. The precipitator has four series fields, two cells in parallel and eight independent bus sections. The collector plates are arranged on 10” spacing and the installed SCA is approximately 144, a size that is common for a unit of that vintage designed for medium to high sulfur coal fly ash.

As with most precipitators of this age the unit has been refurbished with in- kind components and upgraded transformer rectifier controls during its extensive years of service.

Since the firing of low sulfur coal results in lower Sulfur dioxide emissions the unit was switched from firing medium sulfur bituminous coal to low sulfur western PRB coal. The change in fuel, however, produced fly ash with significantly higher resistivity, typically in the order of 2x $10^{12}$ ohm cm. This increase in resistivity resulted in reduced precipitator performance, higher particulate mass emission and hence an increase in stack opacity.

In order to comply consistently with the stack average opacity limit of 20% it was necessary to reduce the boiler /turbine load and its output was limited to 180 MW.

In view of the reduction in load and revenue impact the owner decided to replace the conventional transformer /rectifiers with SIR-E high frequency power supplies. In April 2008 the four transformer rectifiers in fields 1 & 2 were replaced with four SIR-Es each rated at 70KV 800mA and in April 2009 the four transformer rectifiers in fields 3 & 4 were replaced with four SIREs each rated at 60KV 1000mA.

Despite the poor mechanical condition of the precipitator the installation of the SIR-Es enabled the plant to recover 25 MW while keeping the average opacity limited to 13%.

| | | |
|---|---|---|
| Field 1 | 70 kV 800 MA | 70 kV 800 MA |
| Field 2 | 70 kV 800 MA | 70 kV 800 MA |
| Field 3 | 60 kV 1000 mA | 60 kV 1000 mA |
| Field 4 | 60 kV 1000 mA | 60 kV 1000 mA |

Fig. 2.8 Distribution of SIR ratings vs field

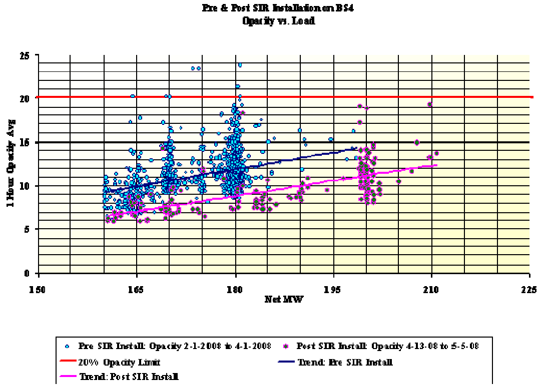


Fig. 2.9 Opacity [%] vs output power [MW], blue line before upgrade, pink line after upgrade

# 3 Discussion

From the presented case studies it can be observed that all meet the results expected from the upgrade projects. However, the performance improvements are capitalized in different ways at the actual sites. At plant A the performance improvement is to be used as a pilot when forced to upgrade the remaining ESPs as a result of more stringent legislations to come. In plant B the improved performance is used to increase fuel flexibility, burning a more difficult coal still meeting the particulate emission limits. In plant C the amount of SO3 injection is minimized or even turned-off, while in plant D and E the performance improvement results in less opacity limited operation and consequently increased revenue due to higher production, i.e. more power delivered to the grid.

# 4 Conclusion

Based on the analysis and evaluation of the presented case studies it is concluded that an upgrade of the energization and control system, combined with a careful tuning of the setup is a very cost effective ESP performance improvement measure. Specifically the tuning of the rapping sequence and the control of the power during the rapping events has proven to be effective in order to achieve lowest possible emission levels.

For plant A, B, and D the upgrade measures include energization, control system, and tuning only, while for the plants B, C, and E also upgrades of ESP internals are included. None of case studies includes extensions of the collecting area.

The discussion in the preceding sections has shown that the final result of an upgrade depends on the ability to build an upgrade package with several technologies put together understanding all aspects of ESP particle collection.

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