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ABSTRACT

The Mercury & Air Toxics Standards (MATS) rule requires coal-fired generating units to comply with emissions limits on filterable particulate matter (PM), acid gases (HCl), and mercury (Hg). The burning of low sulfur fuels, addition of lime-based sorbents for HCl control, and the reduction in SO_3 for Hg control, can all tax the performance of the aging fleet of electrostatic precipitators (ESP).

This paper discusses three projects in which low ripple three-phase power supplies (TPPS) were used as part of the solution in reducing the ESP PM emissions. TPPS have been used on coal-fired boiler ESPs in Europe for many years, and in the past three years, Babcock & Wilcox (B&W) has more than 800 installations in China on cement kiln ESPs. Previous to this writing, there had been no installations of the TPPS in the United States (U.S.).

The first case study involves a U.S. utility that switched fuels for MATS compliance to a low sulfur, low chlorine, and low mercury western bituminous coal. Dry sorbent injection (DSI) utilizing hydrated lime was continuously used for acid gas trim. Prior to this project, the ESP could only achieve opacity compliance, while injecting hydrated lime, at 70% boiler load.

In the second case study, a utility plant needed to eliminate their reliance on an ESP SO_3 conditioning system to reduce the use of activated carbon injection (ACI) for Hg control. Prior to the ESP upgrade, the unit could only achieve full load while utilizing SO_3 to help the ESP's performance. In both the first and second projects, numerous improvements were made to the ESP, including the addition of TPPS, to address MATS compliance.

The third case study describes the simple addition of TPPS to a cement kiln ESP and the resultant increase in ESP power and reduction in PM emissions. This project demonstrates the important role that ESP power supplies play in improving PM collection efficiency.

This paper will identify the prime considerations when upgrading ESPs to achieve lower PM, HCl, and Hg emissions.

INTRODUCTION

To meet particulate matter (PM) requirements of the Mercury and Air Toxics Standards (MATS), stack emissions of filterable particulate must be controlled below a level of 0.030 lb/MMBtu. MATS also requires compliance for acid gases and mercury emissions. Often times the requirements of HCl and Hg control can increase the burden on the ESP for PM removal (flyash + sorbent + reaction byproducts).

The amount of dust that an ESP collects is primarily dependent on the size of the ESP and the amount of effective power that is used to energize the ESP. The size of the ESP is not just its physical size, but rather the physical size in relation to the amount of gas volume that is being treated. This value is commonly referred to as its specific collecting area (SCA), or ft^2 of plate area/1000 acfm.

If in the quest to improve ESP collection efficiency the SCA cannot be increased, then increasing the total power at which the ESP operates has been proven to be the most important parameter. The relationship between specific corona power and collection efficiency has been well researched.[1-3] All of the new power supplies (three-phase power supply [TPPS], high frequency power supply [HFPS], and mid frequency power supplies [MFPS]) offer an improvement in ESP performance.[4] But as of this writing, the TPPS had not yet been proven in a U.S. application.

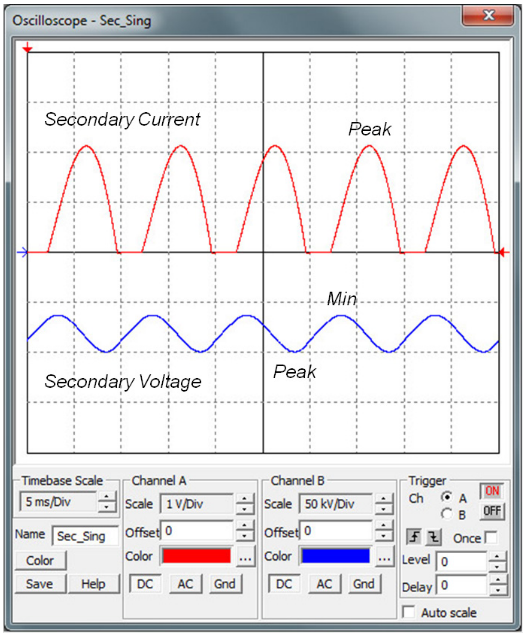
This paper presents three case studies where a TPPS was employed to improve ESP collection efficiency. In some of the projects, the substitution of the traditional single-phase power supply (SPPS) with the TPPS alone reduced PM. In the others, a combination of adding a TPPS and improving the electrical clearances between high voltage and grounded electrodes in the ESP, either by a close attention to re-alignment or a complete replacement of the old electrodes, reduced PM emissions.

This paper will present ways to upgrade the performance of an ESP, including replacement or addition of power supplies, and consider other ESP design parameters that may influence the total power at which the ESP operates.

BRIEF HISTORY OF LOW RIPPLE POWER SUPPLIES

The traditional single-phase precipitator power supply used for years on thousands of ESPs has a voltage waveform with a significant amount of ripple as shown in Figure 1.

Figure 1. Single-Phase Precipitator Power Supply Voltage and Current



The ripple reduces how much power can be applied to the precipitator field. There is a practical limit to how much voltage can be applied to a precipitator field due to sparking, and sparking occurs at the peak of the secondary voltage waveform. The resultant average voltage is always lower than the peak voltage by about 20%. Manufacturers recognized if this waveform could be changed by making the average voltage equal to the peak voltage, significantly more power could be applied to the precipitator field.

Today, in addition to the SPPS with its rippled voltage waveform, a variety of low ripple power supply options are available. Each of these removes the ripple from the secondary voltage waveform and provides a low peak-to-average-voltage ratio. The earliest among these was the high frequency power supply (HFPS). It was designed to provide increased power to the precipitator field while having less size and weight, symmetrical 3-phase load, and higher power factor, all with high reliability.

In actual practice, however, the reliability has been at issue (with a record that is much less impressive than the single-phase precipitator power supply). In addition, there have been grounding and shielding issues coupled with high input and output harmonic distortion.

Based on these experiences, and the many choices available in precipitator power supplies, B&W conducted an internal study in 2014 utilizing power supply electrical mathematical models and laboratory and field testing, to compare different power supply types. Since it had been reported that the Europeans were successfully utilizing TPPS to achieve a low ripple voltage waveform, this type of power supply was also evaluated. The summary of the findings of that study are shown here.[5]

- The increase in corona power from a low ripple power supply can be achieved with several different technologies (HFPS, TPPS, MFPS).
- Modeling data showed that the energy delivered by the precipitator power supply to the spark was insignificant compared to the total energy dissipated by the spark.
- Harmonics are unwanted and have been shown to be a concern on both the input and output of the precipitator power supply. The MFPS and the TPPS produce fewer harmonics.
- Integrating all components into one package (HFPS) has the advantage of the most compact configuration. This can have the disadvantage of placing the control section for the power supply in a harsh environment which affects service life and maintenance.

- Providing a separate transformer and control cabinet (MFPS, TPPS) has the advantage of placing the electronic controls in a controlled environment and allows for duplicate sources of supply. This has the disadvantage of the need for a remote control cabinet and larger size and weight.
- MFPS and TPPS use passive cooling while HFPS designs require active cooling. The increase in components and complexity for active cooling increase cost and maintenance.
- HFPS designs provide low ripple at higher cost, lower reliability, but in a smaller, lighter integrated package.
- MFPS and TPPS provide low ripple at lower average cost, higher reliability, but in a larger, heavier package with a separate control cabinet.
- The HFPS, MFPS, and TPPS provide the lowest ripple voltage on an ESP load.
- The field test showed the TPPS produced an average 50% higher power in the ESP compared to the single-phase precipitator power supply. This suggests that like other low ripple power supplies, the TPPS can produce higher ESP collection efficiencies.

FOR BEST EFFICIENCY, THE ESP MUST BE IN GOOD CONDITION

Achieving a PM limit of 0.030 lb/MMBtu will depend on a number of factors:

1. The amount of dust coming into the ESP
2. The resistivity of that dust
3. The gas volume to the ESP
4. The gas flow quality in terms of uniformity, sneakage, and re-entrainment
5. The quality of the electrical energization
6. The rapping system and program

Improving precipitator efficiency is not guaranteed by simply changing the ESP power supply. The ESP has to be in good physical condition, starting with the electrical alignment between the high voltage (HV) and grounded electrodes (plates). As designed, all HV electrodes in an ESP are exactly the same distance from the plates.

Case Study #1, as an example, originally had 21SPPS. In anticipation of a change to a lower sulfur coal to meet the acid gas requirements of MATS, the ESP was repowered keeping 12 SPPS and adding 15HFPS for a total of 27 power supplies. No other work was done mechanically to the ESP and even with the increase in installed power and electrical sectionalization, the ESP still could not handle the new lower sulfur coal. At the next outage the HFPS were replaced, and the new configuration resulted in 14 TPPS (1 less than the HFPS) and 10 SPPS and new ESP internals (plates and rigid electrodes). With the new configuration the ESP now runs at <4% opacity with the low sulfur coal and hydrated lime injection.

Warped Plates/Electrode Alignment – The alignment between the HV and grounded electrodes will determine the maximum voltage at which that electrical section can operate, be it a SPPS, MFPS, HFPS, or a TPPS. The latter three will run at roughly 20% more voltage because of the low ripple, but their full potential is not achievable because of the limiting value of the spark over voltage. In Case Study #1the TPPS eliminated the performance issues of the HFPS and the new ESP internals allowed the ESP to "power up."

Gas Flow Distribution – Another factor critical to ESP performance is uniform gas flow distribution. Improving gas distribution can reduce outlet emissions by as much as 50%.[6] The ESP may not have been built with the proper turning vanes, perforated plates, and baffles. Even if they were properly designed, ash may deposit on these devices to the extent that it changes the gas flow distribution, lowering the ESP collection efficiency.

Operation of the boiler at low loads may result in lower gas velocities where ash can fall out, creating dust mounds, fouling the gas distribution. These dust mounds may remain once the unit returns to higher velocities and full load. Then when the unit cycles back to low load the mounds can become larger until they reach an equilibrium state. Finally, the gas distribution devices must be kept clean through the use of rappers, vibrators, air cannons, or sonic horns. Proper gas flow distribution can be achieved by conducting either physical or mathematical modeling of the ESP and its ductwork. Those models should be followed up with a field measurement of the gas distribution once the flow correcting devices have been installed.

Ineffective Rapping System – Heavy dust buildup on the plates and HV electrodes can also reduce the sparkover voltage, limiting power into the field. An old rule of thumb calls for 0.25 in. (6.4 mm) buildup or less as being evidence of a proper cleaning system. Problems in rapping can originate in the design, where the proper density of rappers should be at 1500 ft^2 (139 m^2) or less per rapper. It also can occur in the rapper program set up either not providing enough intensity in the rapper impact and/or allowing too long a time before the rapping sequence repeats.

Some responses to MATS compliance requirements may involve fuel switching to a lower chlorine coal which in most cases means a lower sulfur coal. If in the burning of these coals the SO_3 concentration in the gas stream decreases, the ash that the ESP collects can become more and more resistive to current flow in the precipitator. That resistance to current flow over the surface of the ash layer makes the ash more difficult to dislodge. Increasing rapper impact intensity and frequency alone may not be enough to overcome a tenacious ash layer. Reduced power or power off rapping may need to be employed to assist in removing this ash layer. In "removing power" on the section being rapped, the clamping force of the electric field is removed and the rapping becomes much more effective.

Transformer-Rectifier (TR) Sets Nameplate Limited – Since increasing ESP power is a desirable goal to increase ESP efficiency, a close examination must be made of the existing ESP power levels. If some of the existing TR sets are nameplate limited (usually outlet fields in conductive dust applications), changing the size or adding an additional power supply could increase the total power.

As an example, say the existing 400V, 120A, 45KV, and 750mA set is dual bushing and runs at 320V, 120A, 39KV, and 700mA. That set is primary current limited at 120A. If energizing one of the two bushings only results in the set running at 340V, 80A, 41KV, and 500mA, then the TR set is most probably undersized and in most cases adding another power supply in parallel will increase the total power to the ESP. With only one bushing energized, it is running at more than half of the primary current value of that TR set with both bushings on. The TR set is undersized and only has enough rating capacity for energizing a smaller area of the ESP.

Air Inleakage – Air leaking into the flues prior to the ESP or at the ESP (with a high negative pressure) can have a very deleterious effect on efficiency. First, it adds to the gas volume which increases the velocity of the flue gas and therefore reduces the treatment time that the dust is in the ESP. Second, in most cases ambient air dries out the flue gas at the point of entry, making it an area of higher dust resistivity. The higher resistivity zones may reduce the sparkover voltage for the whole electrical section because of that one compromised area.

Temperature Maldistribution – Rotating regenerative air heaters preceding large, wide ESP boxes can introduce dramatically different ash resistivities across the face of the box. A temperature difference of 65F (36C) for example (280F [138C] on the cold end and 345F [174C] on the hot end) is not uncommon. TR sets in the 280F (138C) lane might all run at full current, whereas the sets in the 345F (174C) lane might be spark limited at half the power of the full current lane. If a TR set energizes multiple lanes across the ESP, its performance will be dictated by the limited zone.

DSI AND Hg CONTROL CAN ALSO IMPACT THE ESP EFFICIENCY

The MATS rule requires generating units to comply with emissions limits of particulate matter (PM), hydrogen chloride (HCl), and mercury (Hg). To meet the HCl and Hg requirements the boiler may need to fire coals with a lower chlorine and mercury content, if the unit does not have a scrubber. Often times these new coals are also lower in sulfur content. Dry sorbent injection (DSI), such as hydrated lime or trona, may need to be added to the gas stream ahead of the ESP to further reduce the HCl. Activated carbon injection (ACI) may be needed for further mercury trim.

Lower Sulfur Coals – The lower the sulfur content of the coal, the lower the SO_3 concentration in the flue gas. A cold-side ESP is mainly dependent on SO_3 to aid in conducting current over the surface of the ash particles in the ash layer on the ESP plates to ground. The less SO_3 present in the flue gas, the higher the resistivity of the ash and the lower the sparkover voltage in the ESP. This leads to lower power levels in the ESP and lower particulate collection efficiency. Resistivity plays a critical role in ESP performance and must be closely evaluated.

Sorbents – The sorbents also have an impact on the resistivity of the fly ash. In general, hydrated lime will increase the resistivity of the fly ash, and the extent to which this occurs is dependent on how much must be injected. Some manufacturers offer a coated hydrated lime that has a lower resistivity. Trona has an opposite effect and tends to decrease resistivity.[6] Both sorbents will increase the dust loading to the ESP, but this effect is minor compared to the potential change in resistivity. One reason for this is that sorbents have a larger particle size distribution and for an ESP, larger particles are easier to collect.

In almost all cases, ACI lowers the resistivity of the fly ash and has no impact on ESP performance. Possible exceptions to this statement are ESPs with extremely high velocities (greater than 6 ft/s [1.8 m/s]) or those with poor aspect ratios.

Higher Ash or Lower Heating Value Coals – Besides lower sulfur coals and the problem they present to the ESP with higher resistivity, the solution for HCl and/or Hg compliance might lead to the use of coal with a lower heating value or higher ash content. The lower heating value means more coal will need to be burned and more combustion air will be required to burn that coal. The net result is a higher gas volume to the ESP, lower SCA, and lower treatment time.

The coal with higher ash content will lead to more dust content at the ESP inlet. If the ESP efficiency stays the same, this will lead to higher mass emissions. Often times the efficiency of the ESP can increase with a higher inlet loading because of the increase in space charge (higher kV per unit current), but that increase may not be enough to overcome the increased dust burden.

CASE STUDY NO. 1: DSI AND ACID GAS COMPLIANCE

The Process – The unit has a tangentially fired boiler with a turbine/generator rating of 395 MW gross. The unit is ID fan limited in the warmer summer months to approximately 380 MW. The boiler has low NO_x burners with overfire air for NO_x control. For MATS compliance, the plant will use facility averaging. Hydrated lime is continuously injected at a rate of 100 to 200 lb/h for HCl trim. An ACI system was installed and tested for Hg trim, but is used only when needed.

The coal burned has an ultra-low chlorine and mercury content and is a blend of low sulfur western bituminous coals, 20 Mile (with 10.0% ash, 0.43% sulfur, and 1.2% sodium) and West Elk (with an average of 9% ash, 0.5% sulfur, and 2% sodium). Because of poor ESP performance during previous test burns with western bituminous coals, the utility developed a fallback position by testing a Wahlco SO_3 conditioning system (2 to 8ppm at the air heater outlet) and a BoldEco ammonia conditioning system (1 to 3ppm at the ESP inlet).

The unit typically operated at a very high gas outlet temperature (because of a shortened economizer) and still does even after recent air heater improvements. For example, at 379 MW, ESP inlet temperatures were 356F (180C) on the 1A (east) side and 324F (162C) on the 1B (west) side.

The Precipitator – The ESP was originally a weighted wire unit designed by Buell, with 21 SPPS. In spring 2014, the unit was re-powered with 15 HFPS and 12 SPPS. The internals of the ESP were not replaced at that outage. Reliability and performance problems with the HFPS units precipitated the change to the TPPS.

During the spring 2015 outage, the complete ESP internals were replaced because of very serious corrosion and alignment issues. The 9 in. (229 mm) weighted wire design was replaced with rigid discharge electrodes (RDE) on 11 in. (279 mm) centers. The before and after mechanical configurations are summarized in Figure 2.

Figure 2. Case Study 1 ESP Design Before/After 2015 Outage

DESCRIPTION	BEFORE	AFTER
MW AT TYPICAL FULL LOAD	375	375
ESP BOXES PER UNIT	1	1
CHAMBERS/BOX	6	6
MECH FIELDS/CHAMBER	10	10
FIELD WIDTH (FT)	3	3
FIELD HEIGHT (FT)	31	31
GASS PASSAGES/CHAMBER	40	32
GAS PASSAGE WIDTH (IN.)	9	11
TOTAL PLATE AREA (FT^2)	446400	357120
DISCHARGE ELECTRODE	WIRE	RDE
NO. CONVENTIONAL TR SETS	12	10
NO. HIGH FREQUENCY TR SETS	15	0
NO. 3 PHASE TR SETS	0	14
SCA_9	263	257
GAS VOLUME (ACFM)	1700000	1700000
GAS VELOCITY	5.1	5.2
TREATMENT TIME	5.9	5.8

In addition, outage work included replacement of air heater baskets and seals which resulted in a net drop of 30F (17C) in the gas outlet temperature of both Ljungstrom® air heaters. A large number of leaks in the duct work from the boiler to the ESP were also patched and repaired. New hopper level indicators were installed.

The ESP has six chambers with 10 electrical bus sections in the direction of gas flow. There are a total of 10 SPPS and 14 TPPS. Voltage is controlled with B&W's SQ-300®*i* automatic voltage controllers (AVC). All TR sets communicate with a B&W Precipitator Manager™ data logger/central control computer.

There are 32 gas passages at 11 in. (279 mm) spacing per chamber. The collecting fields are 9 ft (2.7 m), 12 ft (3.7 m), 9 ft (2.7 m) wide by 30 ft-10 in. (9.4 m) tall. The high voltage electrodes are B&W's V-pin arrangement RDEs in electrical bus sections one through four. B&W's opposed pin RDEs are utilized in electrical bus sections five through ten. The plates and RDE electrodes are cleaned with MIGI-style rappers. The rapper control is also part of the Precipitator Manager software. A power-off rapping routine is employed for all fields except the outlet field when the unit load is below 150 MW. When the load exceeds 150 MW, the default non-power off routine is loaded automatically. The force and frequency of both routines are aggressive to effectively remove the higher resistivity ash.

Figure 3 illustrates the layout of the ESP prior to the 2015 upgrade showing the size of the bus sections, chambers, and type of power supply and sectionalization. Figure 4 shows the powering configuration after the outage.

Figure 3. Case Study 1 ESP Powering before the 2015 Outage

<table>
<tr><td rowspan="10">GAS FLOW</td><td colspan="2">U1 SMPS</td><td colspan="2">V1 SMPS</td><td colspan="2">W1 SMPS</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1R 1ph 45KV 1100MA</td><td colspan="2">1S 1ph 45KV 1100MA</td><td colspan="2">1T 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1N 1ph 45KV 1100MA</td><td colspan="2">1P 1ph 45KV 1100MA</td><td colspan="2">1Q 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1K 1ph 45KV 1100MA</td><td colspan="2">1L 1ph 45KV 1100MA</td><td colspan="2">1M 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2" rowspan="2">1G 1ph 45KV 1400MA</td><td colspan="2" rowspan="2">1H 1ph 45KV 1400MA</td><td colspan="2" rowspan="2">1J 1ph 45KV 1400MA</td><td>3' X 31'</td></tr>
<tr><td>3' X 31'</td></tr>
<tr><td colspan="2">D2 SMPS</td><td colspan="2">E2 SMPS</td><td colspan="2">F2 SMPS</td><td>3' X 31'</td></tr>
<tr><td colspan="2">D1 SMPS</td><td colspan="2">E1 SMPS</td><td colspan="2">F1 SMPS</td><td>3' X 31'</td></tr>
<tr><td colspan="2">A2 SMPS</td><td colspan="2">B2 SMPS</td><td colspan="2">C2 SMPS</td><td>3' X 31'</td></tr>
<tr><td colspan="2">A1 SMPS</td><td colspan="2">B1 SMPS</td><td colspan="2">C1 SMPS</td><td>3' X 31'</td></tr>
<tr><td></td><td>40 g.p. @ 9"</td><td>40 g.p. @ 9"</td><td>40 g.p. @ 9"</td><td>40 g.p. @ 9"</td><td>40 g.p. @ 9"</td><td>40 g.p. @ 9"</td><td></td></tr>
</table>

Figure 4. Case Study 1 ESP Powering after the 2015 Outage

<table>
<tr><td rowspan="10">GAS FLOW</td><td colspan="2">1U 1ph 45KV 1100MA</td><td rowspan="2">1S2 1ph
45KV 1100MA</td><td rowspan="2">1V1 1ph
45KV 1100MA</td><td colspan="2">1W 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1R 1ph 45KV 1100MA</td><td colspan="2">1T 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1N 1ph 45KV 1100MA</td><td rowspan="2">1L2 1ph
45KV 1100MA</td><td rowspan="2">1P1 1ph
45KV 1100MA</td><td colspan="2">1Q 1ph 45KV 1100MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2">1K 3ph 70KV 800MA</td><td colspan="2">1M 3ph 70KV 800MA</td><td>3' X 31'</td></tr>
<tr><td colspan="2" rowspan="2">1G 3ph 70KV 800MA</td><td rowspan="2">1H2 3ph
70KV 800MA</td><td rowspan="2">1H1 3ph
70KV 800MA</td><td colspan="2" rowspan="2">1J 3ph 70KV 800MA</td><td>3' X 31'</td></tr>
<tr><td>3' X 31'</td></tr>
<tr><td colspan="2" rowspan="2">1D 3ph 70KV 1300MA</td><td rowspan="2">1E2 3ph
70KV 800MA</td><td rowspan="2">1E1 3ph
70KV 800MA</td><td colspan="2" rowspan="2">1F 3ph 70KV 1300MA</td><td>3' X 31'</td></tr>
<tr><td>3' X 31'</td></tr>
<tr><td colspan="2" rowspan="2">1A 3ph 70KV 800MA</td><td rowspan="2">1B2 3ph
70KV 400MA</td><td rowspan="2">1B1 3ph
70KV 400MA</td><td colspan="2" rowspan="2">1C 3ph 70KV 800MA</td><td>3' X 31'</td></tr>
<tr><td>3' X 31'</td></tr>
<tr><td></td><td>32 g.p. @ 11"</td><td>32 g.p. @ 11"</td><td>32 g.p. @ 11"</td><td>32 g.p. @ 11"</td><td>32 g.p. @ 11"</td><td>32 g.p. @ 11"</td><td></td></tr>
</table>

Reliability and Performance – The plant needed to change fuels to a low sulfur western bituminous coal to address MATS rules. Because of the higher resistivity of this coal, the unit could only run at 70% of full load with hydrated lime injection, while staying under the opacity limit of 20%. The ESP was repowered with HFPS in 2014, but still could not achieve full load and stay within opacity limits. Unfortunately, the HFPS suffered reliability issues, cross talk with existing AVCs, and grounding problems. In addition to those problems, the ESP internals were in disrepair.

During the 2015 outage the HFPS were replaced with TPPS and the ESP internals were replaced with new collecting plates and RDEs. The unit can now run at full load, burning low sulfur Colorado bituminous fuel with continuous hydrated lime injection and opacities under 4%. The TPPS ran at much higher power levels than the HFPS, but that is at least partially due to the new ESP internals. The ESP power density before and post outage was 0.16 and 1.40 w/ft^2, respectively. There were no failures or start-up problems with the TPPS, nor interference with the SPPS. The ESP fields have had 100% availability.

Power off rapping routines were utilized during low load operation. This rejuvenation period is crucial for sustainable performance over long-term operation. The total ESP power has increased significantly since the outage as shown in Figure 5 (pre-outage) and Figure 6 (post-outage).

Figure 5. Case Study 1 – ESP Performance Pre-Outage

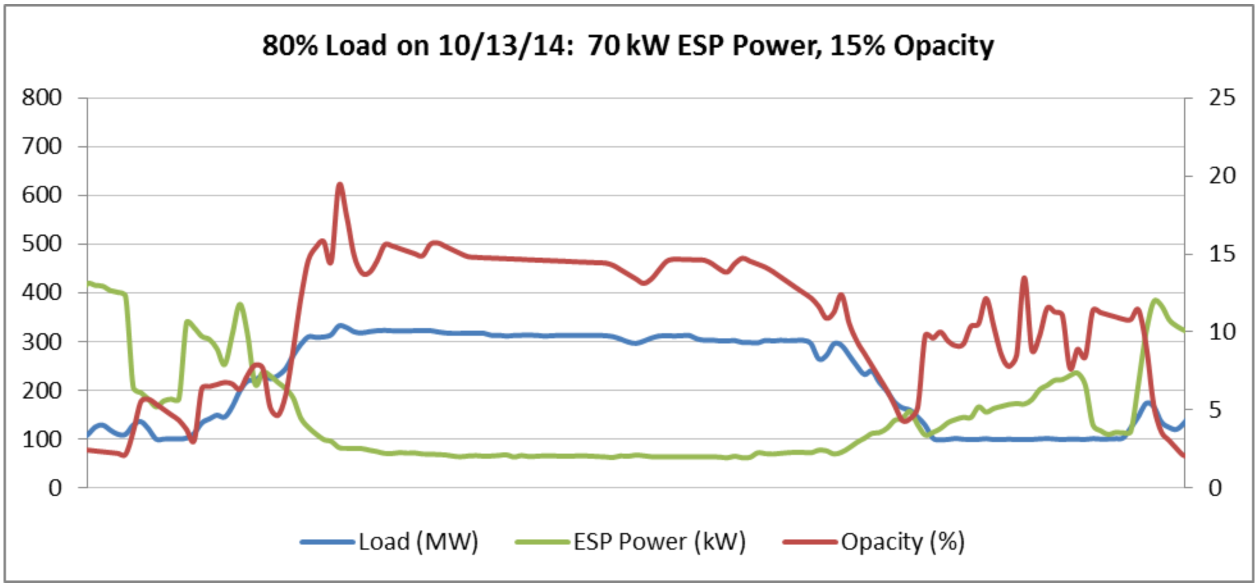
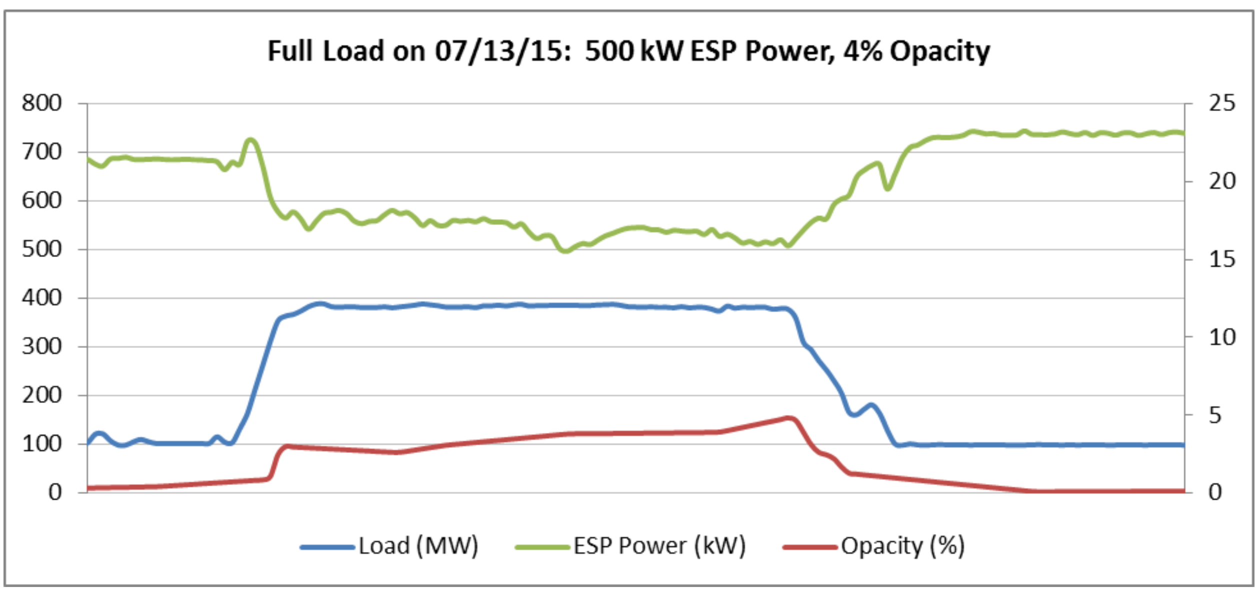


Figure 6. Case Study 1 – ESP Performance Post-Outage



CASE STUDY NO. 2: SO_3 INTERFERING WITH ACI

The Process – The unit has a tangentially fired boiler with a turbine/generator rating of 100 MW gross. The boiler has low NO_x burners with overfire air for NO_x control. For mercury control, ACI is injected at a rate of 150 to 400 lb/day after the air heater, before the ESP. Also, $CaBr_2$ is added to the coal feeders at an approximate rate of 23 ppm to enhance mercury capture. The coal burned is a PRB Black Thunder with 4–5% ash, 0.20% sulfur, and 1.0 to 1.3% sodium. If opacity is high, the unit has the capability of co-firing coal with natural gas.

The unit is equipped with two parallel tubular style air heaters designated as the A and B sides. ESP inlet temperatures can range from 300 to 340F (149 to 171C) on the B side and 340 to 380F (171 to 193C) on the A side. After the air heaters, the gas stream is combined and treated by a Multiclone® dust collector, then splits to the two ID fans, then to the ESP. For years, the higher ash resistivity was combatted and ESP performance was enhanced by injecting SO_3 into the gas stream. Because of the interference of SO_3 with mercury capture, the SO_3 system was replaced with a flue gas conditioning agent to modify fly ash resistivity. This system has been turned off since the ESP has been retrofitted, as described further below.

The Precipitator – The ESP was originally designed by Research Cottrell, had eight TR sets, and an original SCA of 261_9 (normalized to a gas passage width of 9 in.). It has two chambers with four mechanical and seven electrical fields in the direction of gas flow, with eight bus sections in the direction of gas flow. There are a total of 10 SPPS controlled by SQ-300 AVCs. In addition, there are four TPPS (70kV, 400mA) added to the first mechanical fields and are controlled by SQ-300*i* AVCs.

All TR sets communicate with a B&W Windac® data logger/central control computer.
There are 31 gas passages at 9 in. (229 mm) spacing per chamber. Each field is 9 ft wide by 24 ft tall (2.7 x 7.3 m). The high voltage electrodes are rigid discharge electrodes, installed in 2005 while retaining the original collecting plates. In 2008, new collecting plates and electrodes were installed, retaining the gas passage spacing. The plates and electrodes are cleaned with MIGI-style rappers. The rapper control is a B&W Winrap design. A power off rapping program is employed for all fields of the ESP, on a 24-hour per day basis.

Figure 7 illustrates the layout of the ESP prior to the 2015 ESP upgrade showing the size of the bus sections, chambers, and type of power supply energizing each section. Figure 8 shows the powering configuration after the upgrade. Figure 9 lists the ESP design data, before and after the upgrade.

Figure 7. Case Study 2 – ESP Performance Pre-Outage

	#9 TR 45KV, 750MA	#10 TR 45KV, 750MA	4.5' x 24'
	#5 TR 45KV, 750MA	#1 TR 45KV, 750MA	4.5' x 24'
	#6TR 45KV, 750MA	#2TR 45KV, 750MA	9' x 24'
	#7TR 45KV, 1000MA	#3TR 45KV, 1000MA	9' x 24'
GAS FLOW	#8TR 45KV, 750MA	#4TR 45KV, 750MA	9' x 24'
	31 g.p.@9"	31 g.p.@9"	

Figure 8. Case Study 2 – ESP Performance Pre-Outage

	#9 TR 45KV, 750MA	#10 TR 45KV, 750MA	4.5' x 24'
	#5 TR 45KV, 750MA	#1 TR 45KV, 750MA	4.5' x 24'
	#6TR 45KV, 750MA	#2TR 45KV, 750MA	9' x 24'
	#7TR 45KV, 1000MA	#3TR 45KV, 1000MA	4.5' x 24'
	#8TR 45KV, 750MA	#4TR 45KV, 750MA	4.5' x 24'
	#14 3ph 70KV, 400MA	#12 3ph 70KV, 400MA	4.5' x 24'
GAS FLOW	#13 3ph 70KV, 400MA	#11 3ph 70KV, 400MA	4.5' x 24'
	31 g.p.@9"	31 g.p.@9"	

Figure 9. Case Study 2 ESP Design Data

DESCRIPTION	BEFORE	AFTER
MW AT TYPICAL FULL LOAD	100	100
ESP BOXES PER UNIT	1	1
CHAMBERS/BOX	2	2
MECH FIELDS/CHAMBER	4	4
FIELD WIDTH (FT)	9	9
FIELD HEIGHT (FT)	24	24
GASS PASSAGES/CHAMBER	31	31
GAS PASSAGE WIDTH (IN.)	9	9
TOTAL PLATE AREA (FT^2)	107136	107136
DISCHARGE ELECTRODE	ELEX	ELEX
NO. CONVENTIONAL TR SETS	10	10
NO. HIGH FREQUENCY TR SETS	0	0
NO. 3 PHASE TR SETS	0	4
SCA_9	265	265
GAS VOLUME (ACFM)	405000	405000
GAS VELOCITY	6.0	6.0
TREATMENT TIME	6.0	6.0

<u>Reliability and Performance</u> – A PM test was conducted prior to the ESP upgrade. The test was to see how well the unit could perform without the conditioning agent to modify ash resistivity. The unit could not achieve peak load and maintain less than 20% opacity without co-firing natural gas with coal. The average PM was 0.026 lb/MMBtu and opacity of 21.7%. The unit was retested several months later, this time with the conditioning agent. No natural gas was required to meet load and an average of 45.1 t/hr coal flow was used. The average PM was 0.021 lb/MMBtu and opacity of 8.2%.

Approximately one week after the ESP upgrade outage (detailed in Figure 9), the unit was retested at full load on coal only, with no conditioning agent. The average opacity was in the 5 to 7% range. Project goals were met and the unit was able to run without SO_3 conditioning or conditioning agent.

Although the ESP internals were not replaced, as was the situation in Case Study 1, the ESP internal alignment was closely checked and corrected as much as possible. Some gas flow distribution devices were added, as were all new voltage and rapper controls. An aggressive power-off rapping routine was incorporated. No problems with any of the controls or power supplies have been reported since start-up in 2015. In 2014 during peak loads of about 96 MW, average opacity typically ranged between 13 and 17%. For 2015 at similar loads, average opacity typically ranged between 4 to 7%, a significant improvement.[5] The ESP power density pre and post outage was 1.15 and 2.37 w/ft^2, respectively.

CASE STUDY NO. 3: INCREASE IN ESP POWER LOWERS EMISSIONS

The Process – The third case study involves an ESP on a preheater cement kiln in Anhui Province in China. A cement kiln is a refractory-lined steel tube, sloped at about a 4-degree angle, which rotates between 50 and 200 revolutions per hour (rph). Raw mix is added at the top end and pulverized coal fires the kiln from the lower end. Several stages of cyclones are positioned at the top end of the inclined kiln to preheat the raw material. The ESP is located after the kiln gases exit the preheater tower.

This kiln has a production capacity of 4,500 tons per day. The ESP was designed for PM emissions of 50 mg/Nm^3, but was tested at 72 mg/Nm^3 prior to the ESP upgrade. The owner wished to reduce PM emissions to 30 mg/Nm^3 or lower.

The Precipitator – The ESP was originally designed by Sinoma (Henan) Environmental Protection Co., LTD. It had eight SPPS, and an SCA of 843_9. It has two chambers with four mechanical and four electrical fields in the direction of gas flow. The owner considered four solutions to lower PM emissions: 1) convert ESP to fabric filter baghouse, 2) add ESP fields, 3) replace the SPPS with HFPS, or 4) replace the SPPS with TPPS. The most economical approach was chosen: replacing all 8 SPPS with 8 TPPS and new B&W SQ-300*i* AVC controls. No other changes were made to the ESP. Figure 10 lists the ESP design data, before and after the upgrade.

Figure 10. Case Study 3 ESP Design Data

DESCRIPTION	BEFORE	AFTER
ESP BOXES PER UNIT	1	1
CHAMBERS/BOX	2	2
MECH FIELDS/CHAMBER	4	4
GAS PASSAGE WIDTH (IN.)	15.75	15.75
TOTAL PLATE AREA (FT^2)	239711	239711
DISCHARGE ELECTRODE	RIGID FRAME	RIGID FRAME
NO. CONVENTIONAL TR SETS	8	0
NO. 3 PHASE TR SETS	0	8
SCA_9	843	843
GAS VOLUME (ACFM)	502959	502959
GAS VELOCITY (FT/SEC)	2.7	2.7
INSTALLED CURRENT DENSITY (uA/FT2)	33.4	40.0

Performance – A PM test was conducted after the ESP upgrade. The unit tested at 10.79 mg/Nm^3, much better than the owner expected. A second test was conducted by the controlling environmental protection agency and produced identical results. That testing was conducted in 2014 and recent testing resulted with PM between 10 to 20 mg/Nm^3.

ESP power levels at full kiln load were taken before and after the installation of the TPPS and appear in Figure 11. As shown, by changing out the power supplies to TPPS, the ESP power almost tripled, resulting in the reduction in PM emissions.

Figure 11. Case Study 3 ESP Before/After Power Levels

PREHEATER CEMENT KILN ESP	SPPS (BEFORE)			TPPS (AFTER)		
	KV	mA	KW	KV	mA	KW
TR Nameplate Rating	72	1000	72	80	1200	96
1-1 field	40	320	12.8	65.5	327	21.4
1-2 field	52	320	16.6	63.5	1100	69.9
1-3 field	69	500	34.5	56	1060	59.4
1-4 field	58	380	22.0	61.9	1015	62.8
2-1 field	52	240	12.5	65	426	27.7
2-2 field	58	400	23.2	63.5	1102	70.0
2-3 field	32	480	15.4	57.4	1032	59.2
2-4 field	66	260	17.2	64.8	980	63.5
		TOTAL KW	154.2		TOTAL KW	433.9
		W/FT^2	0.64		W/FT^2	1.81

SUMMARY

Three case studies were reviewed to evaluate the role of ESP power in improving ESP collection efficiency and therefore, lowering PM emissions. In each case the ESP power density was increased dramatically, resulting in lower PM emissions or ability to accommodate different coals and sorbents and still meet the PM requirements. The results show that:

	POWER DENSITY (W/ft^2)	
CASE STUDY	BEFORE	AFTER
1	0.16	1.40
2	1.15	2.37
3	0.64	1.81

- In case study 1, the addition of low ripple power supplies (HFPS) alone did not lower PM emissions. The poor internal conditions of the ESP also had to be addressed. In addition, a power off rapping routine at low boiler load allowed the ESP power to recover on a daily basis. This rejuvenation period is crucial for sustainable performance over long-term operation with higher resistivity fuels.
- More than 900 installations of TPPS have demonstrated reliability. The availability of all sections of an ESP allows plant owners to achieve maximum PM reduction.
- In case study 2, the ESP internals did not require replacement, but had to be re-aligned to boost ESP power. The increased electrical sectionalization and increased power from the

TPPS enabled the ESP to operate without the addition of a resistivity conditioning agent. Power off rapping at low loads was again a critical tool in sustaining ESP performance.

- In case study 3, replacing the SPPS with TPPS alone reduced the PM emissions. The TPPS with its low ripple voltage waveform, along with new automatic voltage controls, tripled the power to the ESP. In this case, the ESP internals were in good condition and the SCA of the ESP (843_9) was quite large.
- Case studies 1 and 2 both emphasize the importance of the design details and electrical alignment within the ESP in determining total ESP power and overall collection efficiency.

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