

SMPS: Present Application & Future Investigation

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Abstract

This paper discusses Switch Mode Power Supply for improved energization of electrostatic precipitators and particulate matter collection efficiency enhancement. The paper includes discussions of present day applications and planned future investigations.

Background

In 1999 only two demonstration Switch Mode Power Supply (SMPS) units were in operation. Significant production commenced at NWL in 2000 and by mid-2005 there were 215 SMPS units in service. Today, there are well over 1000 SMPS units operating worldwide.

SMPS is an electrostatic precipitator (ESP) energization system that incorporates three-phase power supply. It delivers high frequency energization that is spark-regulated and otherwise controlled by means of digital signal processing (DSP).

The advantage of three-phase power supply is to provide higher efficiencies (i.e., higher power factors), a balanced load, and reduced secondary voltage waveform ripple. The advantage of high frequency energization is to further reduce waveform ripple and also to allow faster and superior control over the secondary voltage waveform from d-c mode through to intermittent energization (IE) mode. Spark-regulation mode enables the control system to manipulate ramp rates so that an ESP's bus section can operate at a pre-selected spark rate if that is the operator's preferred mode of operation. And DSP is a control system with a fast response time of 30 microseconds versus 8.33 milliseconds for conventional 60 Hz power supplies. Table 1 presents a brief comparison between SMPS and conventional 60 Hz power supplies.

Because the SMPS unit's a-c input voltage is rectified, filtered, and then switched at 25 kHz, the percentage ripple in secondary voltage waveform (kV_{p-p}) is only 3 to 5% of d-c voltage as compared to 35 to 45% for conventional 60 Hz power supplies (see Figure 1). Reduced secondary voltage waveform ripple allows the ESP to operate at 10 to 20% higher secondary voltage levels. This is a key contributor to enhanced ESP performance.

Ripple Effect

There is no evidence in the literature supporting the claim that high frequency energization in and of itself provides enhanced ESP performance. However the literature overwhelmingly calls for higher average secondary voltages and higher peak secondary voltages as a means towards increasing particle charging and migration, key steps in the precipitation process, which in turn promotes increased particulate matter (PM) collection efficiency.

When Harry White authored Industrial Electrostatic Precipitation in the early 1960s (Ref. 1) he did not have knowledge of future advances in three-phase high frequency energization, but nevertheless there are at least two observations in his section covering sparkover and voltage waveform that directly apply.

White cited field investigations demonstrating that spark rate for many ESPs follows an exponential law:

$$S = e^{b(V_p - V_1)}$$

where:

S = spark rate (sparks per minute)

V_p = peak secondary voltage (kV)

V₁ = spark onset secondary voltage (kV)

b = an empirical constant.

The differential between peak secondary voltage and average secondary voltage contributes to the determination of a bus section's spark rate; as the difference between peak secondary voltage and average secondary voltage at spark onset increases, so does the bus section's spark rate.

If the gap between average and peak secondary voltage can be reduced, then sparking (and sparkover) can be delayed and higher average secondary voltages attained. In practical terms, when a bus section is controlled to maximize corona power on spark regulation mode, as kV_{p-p} decreases, kV_{avg} increases. SMPS energization is capable of accomplishing this.

White further wrote that:

Very conductive particles are precipitated best by voltages which approach d-c, and high-resistance particles respond best to fairly impulsive voltages. The former have a waveform factor V_{avg}/V_p which approaches unity, and the latter have a rather low V_{avg}/V_p factor of the order of 0.50 or possibly somewhat less.

The above observation helps to define the range of applicability for three-phase high frequency energization.

Range of Applicability

SMPS has enhanced ESP performance on the following applications:

- Cold-side ESPs on coal-fired boilers firing moderate to high sulfur Eastern bituminous coals
- Cold-side ESPs on coal-fired boilers firing Western subbituminous and Powder River Basin (PRB) coals with moderate to high sodium contents (measured as percent Na₂O in ash)
- Cold-side ESPs on coal-fired boilers that are flue gas conditioned with SO₃
- Cold-side ESPs on boilers that co-fire coal and biomass
- Recovery boiler ESPs (saltcake collection)
- Wood-fired boiler ESPs
- Municipal solid waste incinerator ESPs
- Cement kiln ESPs
- Hot-side ESPs
- Wet ESPs.

ESPs servicing oil-fired boilers, Orimulsion™ fired boilers, other types of biomass fuel boilers, and ESPs downstream of dry scrubbers would also benefit from SMPS energization.

Figure 2 presents a series of secondary average voltage-current curves (V-I curves) that help provide insight into SMPS's range of applicability.

The V-I curves labeled A and B are "healthy" curves, representative of moderate to moderate-low resistivity PM applications; note that as secondary voltage increases, secondary current also increases. All of the above listed ESP applications have V-I curves similar to curves A and B.

V-I curves A and B indicate that SMPS is capable of providing 10 to 20% more average secondary voltage and 60 to 100% more corona power when compared to conventional 60 Hz power supplies. A 10% increase in average secondary voltage is typically equivalent to a migration velocity enhancement factor (w'/w) of 1.20. A recent field startup of a rebuilt ESP with SMPS demonstrated that, when using $w'/w = 1.20$ in a back-calculation, SMPS energization was equivalent to adding one 9-ft long field to the rebuilt ESP energized by conventional 60 Hz power supplies.

The V-I curves labeled D and E are “unhealthy” curves, representative of a high resistivity PM that is depleted of charge carriers. Note that for these curves whenever secondary voltage remains constant or decreases, secondary current increases; this increase in secondary current flow is partially attributable to the generation of positive ions inside the dust layer at the surface of the collecting electrode plates, a phenomenon known as back-corona ionization. The optimum operating point on unhealthy V-I curves is at the knee of the curve, prior to the onset of back corona ionization. SMPS is currently not a reliable solution for ESP performance enhancement when an ESP is collecting high resistivity PM. However, as will be discussed in the Future Strategies section, when SMPS is controlled in IE mode it is capable of providing those “fairly impulsive voltages” described by White.

The V-I curve labeled C represents a borderline scenario where SMPS may or may not provide the desired ESP performance enhancement. PM electrical resistivity is in the approximate range of $8E+10$ to $2E+11$ ohm-cm and application of SMPS requires careful evaluation on a case by case basis.

Occasionally coal-fired boilers are designed to fire a wide range of coals that vary in quality, and given this scenario the potential for ESP performance enhancement when using SMPS must be evaluated on a time-at-fuel basis. As an example, if a generating unit’s range of coal quality can be represented by V-I curves B and C, with curve C representative of only 5% of unit operating time, then it would be an easy decision to install SMPS for purpose of ESP performance enhancement. Other fuel ranges may not be that easy to evaluate. When conducting these evaluations it must be noted that SMPS will never decrease ESP performance when applied to fuels represented by V-I curves C, D and E.

Some ESPs operate with non-ideal conditions such as excessive gas sneakage past collection zones, maldistributed flue gas flow, maldistributed flue gas temperature, etc. In these situations replacing conventional 60 Hz power supplies with SMPS has been field-demonstrated to improve ESP energization and PM collection performance; however the full benefit of SMPS cannot be realized. Potential application of SMPS at these sites requires careful evaluation.

SMPS has been applied to most of the common types of discharge electrode designs: weighted wire, rigid frame, ELEX, pipe & spike, and various high-discharge electrodes in wet ESPs. And collecting electrode plate spacings vary from 9 to 16-inches.

Energy Savings

SMPS is a “green” technology; however the electric energy conservation realized by replacing conventional 60 Hz power supplies (0.63 power factor) with SMPS (0.94 power factor) is dependent on the operator’s desired increase in PM collection performance.

For example if a conventional 60 Hz power supply rated at 1000 ma output is replaced by SMPS at 1000 ma output, then the SMPS delivers 11.8% additional corona power to the ESP while utilizing 21.9% less power feed. A grassroots ESP project will always benefit from this order-of-magnitude electric energy savings.

But it is more common to have higher-output SMPS units replace lower-output conventional 60 Hz power supplies on older, undersized ESPs, so as to fully utilize the technology’s capacity for ESP performance enhancement. When this is the goal, SMPS can deliver up to 100% additional corona power to the ESP and electric power feed will increase significantly. It can be debated, however, that alternative ESP upgrade strategies would require the equivalent or perhaps additional electric power consumption when compared to an SMPS solution.

Future Investigations

Presently it is not completely understood how those applications represented by V-I curves D and E in Figure 2 will be benefited by SMPS in IE mode operation. SMPS applied to high resistivity PM collection will require field-trials.

It is not surprising that in IE mode the SMPS with DSP control provides a faster rise time, a higher peak voltage, and a higher pulse rate than conventional 60 Hz power supplies. SMPS is capable of delivering On Times from 0.10 to 10 milliseconds and Off Times from 0.10 to 99 milliseconds. This compares with one-half cycle (8.33 milliseconds) On Time and one full cycle (16.67 milliseconds) Off Time for a conventional 60 Hz power supply. SMPS provides greater flexibility when in IE mode, with the capability to duplicate 60 Hz IE mode waveforms or produce advanced IE algorithms.

Figure 3 provides a comparison of SMPS operating in DC mode versus IE mode. Figure 3a is an oscilloscope trace of SMPS DC mode operation where $kV_{avg} = 29.4$ and $kV_p = 30.7$. Figure 3b demonstrates IE mode operation with 0.30 milliseconds on-time and 3.3 milliseconds off-time, where $kV_{avg} = 26.6$ and $kV_p = 37.4$. The 21.8% increase in kV_p should provide improved charging and precipitation of high resistivity particles without onset of back corona. The SMPS unit's 3.3 milliseconds off-time will provide additional electric energy savings.

There have been reports of success in Europe and the Pacific Rim when using SMPS in IE mode, but these are not as of yet duplicated within the United States, pending future investigation. One overseas investigator measured an enhancement factor (w'/w) of 1.23 when collecting coal fly ash in the resistivity range E+11 to E+12 ohm-cm, while SMPS in IE mode produced no measurable migration velocity enhancement at E+13 ohm-cm.

Many ESPs operating in the United States are pre-conditioned with SO_3 reagent for purpose of fly ash resistivity moderation. As SO_3 is a known interference when capturing mercury via activated carbon injection, future investigation should be made into minimizing (or eliminating) SO_3 injection by application of PowerPlus in IE mode, and then quantifying the net beneficial effect on PM capture and mercury removal efficiency.

References

1. PowerPlus™ Series – High-Frequency Power Conversion Technology, NWL Product Bulletin No. ET 127
2. White, Harry J., Industrial Electrostatic Precipitation, Addison-Wesley Publishing Company, Inc., 1963
3. NWL Inc. Website

Table 1
Comparison of SMPS to Conventional 60 Hz Power
Supplies for 1000 ma Rating (Ref. 3)

Parameter	SMPS	60 Hz Power Supply
Output Voltage kV dc Average	70	55
Output current ma dc	1000	1000
Output Power kW	70	55
Peak Output Voltage kV	71.8	92.4
% Ripple kVp-p	3-5	35- 45
Input Voltage (VAC)	480	480
Input phases	3	1
Input line current line (AAC)	94.0	227.1
Losses (kW)	4.0	3.5
Power factor	0.94	0.63
Input kVA	78.7	92.2
Operating frequency	25 kHz	60 Hz
Arc shutdown time (msec)	0.03	8.33
Cooling	Forced Air (1/2 HP fan)	Natural Convection
Volume envelope (cubic feet)	24	65
Plan envelope (square feet)	10	21
Weight (lb.)	1000	3860
Oil Reservoir (gallons)	29	135
Wiring from T/R to control	Factory	Field

Figure 1
Comparison of Secondary Voltage Waveforms
Increasing output from top (lowest output) to bottom (highest output)

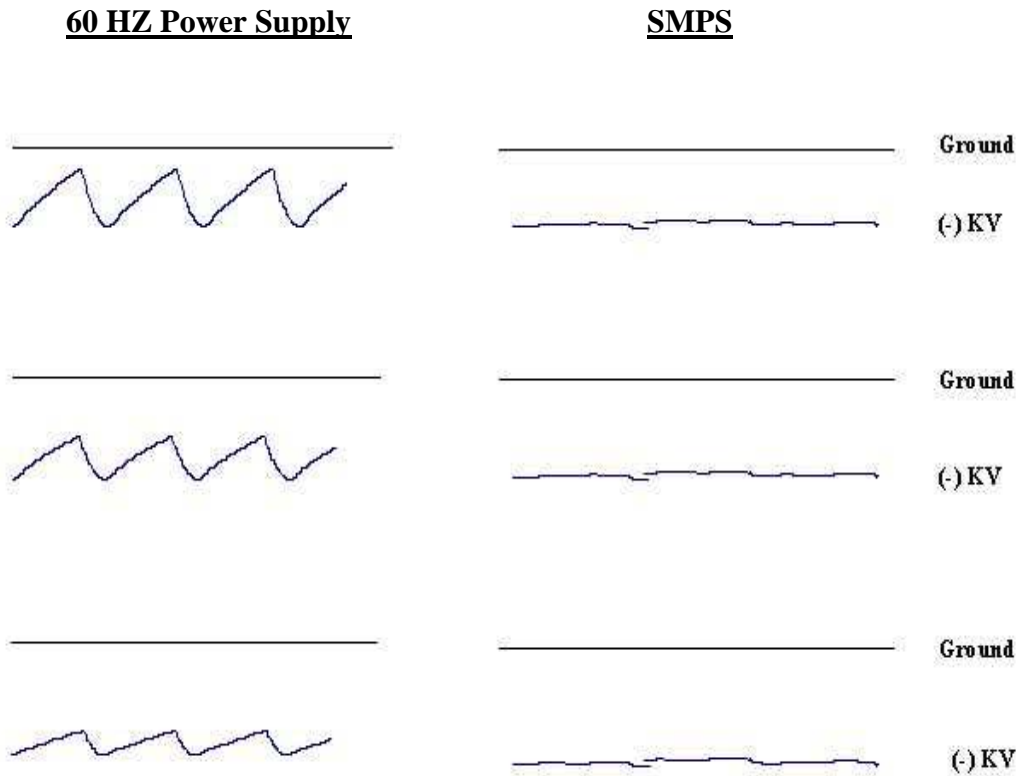


Figure 3 IE with SMPS

Figure 3a - DC mode Operation

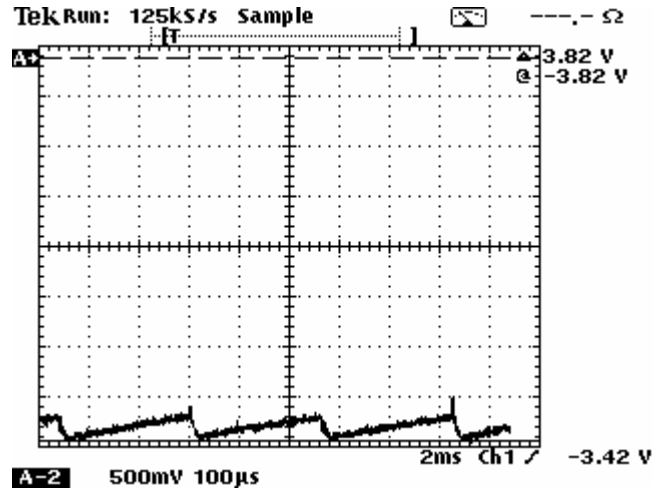


Figure 3b - IE mode Operation

