High Frequency Switch Mode Power Supplies for

Electrostatic Precipitators

Operational and Installation advantages

Robert Guenther
NWL Inc. Bordentown, NJ

November 2004

Introduction

High Frequency Switch Mode Power Supplies (HFSMPS) are being introduced to the electrostatic precipitator market at price points that are very competitive with the linear transformer/rectifier sets and SCR-based controls that have been used in the industry for many years. The new switch mode power supplies have dramatically different performance and physical characteristics than linear power supplies. As applied to the ESP application, these new power supplies will have a major impact on many aspects of precipitator design, construction, operation, and maintenance.

Suppliers and users of ESP's need to become familiar with this new power supply technology, in order to assess the specific effect that its introduction will have on their businesses. This paper provides an overview of the operational and installation advantages of the PowerPlus, NWLs switch mode power supply for ESP (electro static precipitator) applications.

Overview of PowerPlus Technology:

In the 1960s when SCR technology started to replace saturable core reactor controls, there was interest in improved control of the T/R as well as concern about replacing a steel and copper component with a new less proven solid state device. A similar situation exists today. A conventional linear supply consisting of a SCR control, current limiting reactor, and transformer-rectifier set has well established reliability and performance characteristics. HFSMPS products are not yet as well proven.

But consider that PowerPlus technology offers significant performance and installation advantages including-

1. Unmatched flexibility in control of the output voltage waveform from DC to fast IE and anywhere in between including ripple comparable to the conventional solution. This can provide improved particulate collection of with a variety of fossil fuels.

2. PowerPlus units provide more power into the precipitator while consuming less kVA input than conventional systems.

3. PowerPlus units are significantly smaller, lighter, and easier to install and service. They are designed for outdoor service and do not require a climate controlled room.

4. Digital Signal Processing (DSP) based controllers that can sample and process data very fast will be available for PowerPlus in 2005. When combined with the fast switching characteristics of the IGBT devices, even higher performance control algorithms will be possible.

5. PowerPlus technology is still in the early stages of the product life cycle. The power ratings, performance, features, and reliability will continue to improve and expand over time. The conventional power supply technology is very mature and offers little opportunity for any further meaningful improvements. Therefore HFSMPS are expected to soon become the ESP industry standard.

   It is important to mention that installing a conventional SCR-CLR-T/R system will be a significant “sunk cost” that may effectively lock out the ability to take advantage of future PowerPlus advancements for the 10-20 year life of the T/R set.

These performance and installation advantages are discussed further in this paper. Actual operating results from a number of plants are reviewed.

Operational Advantages of PowerPlus:

The PowerPlus has operational advantages that include flexibility of output voltage waveform, fast arc sensing and recovery, and high power factor. Because the unit operates at high frequency and is not restricted to the 60 Hz line frequency limit of ½ cycle (8.33 msec), the output voltage waveform can be adjusted from a nearly pure DC (low ripple) to Intermittent Energization (IE) sawtooth shapes with rise and fall times typically in the low millisecond range (1 to 2 msec).

DC Mode of Operation:

A conventional SCR controller-CLR-T/R system always produces an output voltage that has significant ripple due to its low frequency operation and the use of phase control. Arcing occurs near the peak of the output voltage waveform. As a result, the kVdc (average voltage) and the power into the ESP are limited because of this break-over caused by the much higher peak value.

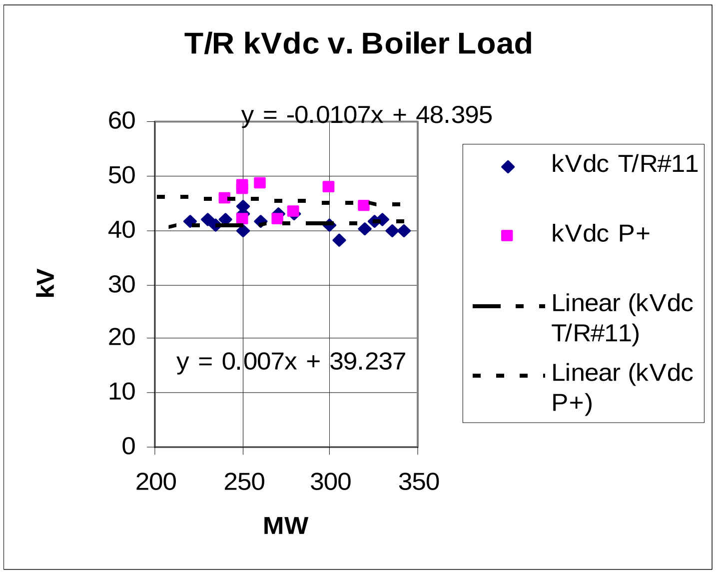
ESP's require voltage to ionize particulate and also to cause migration of the particulate to the collecting plates. The peak voltage drives ionization and the DC level forces migration of particulate. The kV product (kV peak times kV dc) provides an index of relative power supply performance on an ESP.

When low resistivity conditions exist the nearly pure DC output of the PowerPlus offers advantages that conventional systems can not provide. Since the peak and the average are early the same, the kVdc can operate very close to the break over level. This has the potential to increase both the kV product and the power into the ESP. Following is a summary of data obtained from PSE & G's Mercer Generating Station, Southern Company's Savannah River Plant Kraft, and TVA-JOF.

Mercer Generating Station

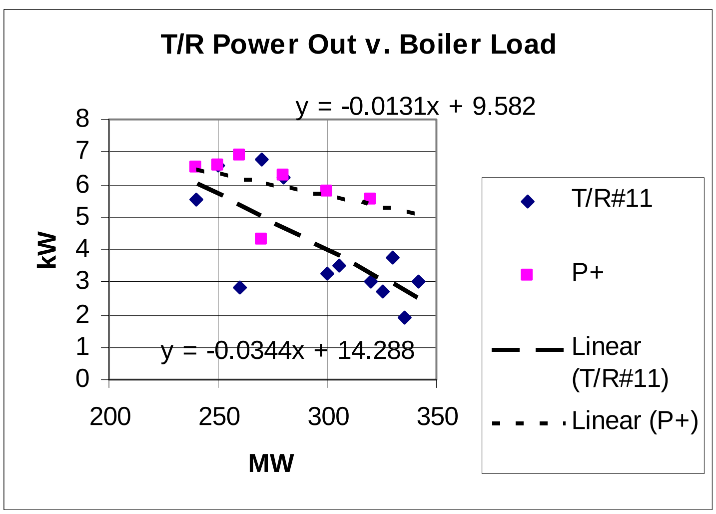
At Mercer Generating Station, a 56 kW PowerPlus unit was installed on an inlet field. Operational measurements were taken and compared to data recorded the previous month from the operation of the conventional unit that was replaced. The following Tables 1-3 show the PowerPlus unit operated with more power into the ESP, at a higher voltage level, and provided more kW into the ESP per kVA required from the feeder source.

Table 1



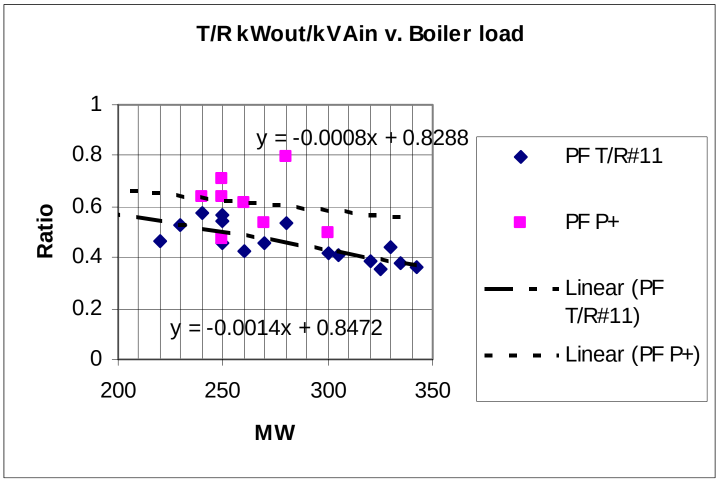
Higher kVdc with PowerPlus

Table 2



Higher kW into ESP with PowerPlus

Table 3



Higher kW into ESP per kVA of input power with PowerPlus

Savannah River Plant Kraft

Table 4 on the following page summarizes data taken after the retrofit of two parallel four-field (in series) ESP's. On the first ESP, the power supplies were four conventional SCR-CLR-T/R systems labeled 3-1 to 3-4. Each T/R had a splitter switch at the output. The second ESP had the first two fields sectionalized with two PowerPlus units each. The two remaining fields had PowerPlus units with splitter switches at the output.

The combination of PowerPlus units 3-5 and 3-6 delivered both a higher kV product and higher kW power to the ESP than did the standard T/R on field 3-1. Similar improved results were obtained for the combined output of 3-7 and 3-8 when compared to 3-2.

The PowerPlus units for 3-9 and 3-10 provided greater kW into the ESP than did the conventional 3-3 and 3-4, but the kV product for each PowerPlus unit was somewhat lower. The reason for this is that the PowerPlus units reached rated output current before reaching arcing/sparking voltage. If the ESP using PowerPlus units had been sectionalized for all fields, then the PowerPlus units would not have been current limited and would have reached higher voltages.

In summary the PowerPlus units at Plant Kraft produced higher kW into the ESP field and a higher kV product. At the same time, the kVA required to power the conventional units 3-1 to 3-4 was 280.7 kVA while the input kVA required for the PowerPlus units was just 196.7 kVA. Thus the plant gets more power into the ESP and higher kV product (unless current limited) for significantly less kVA from the generating equipment. Approximately 735,000 kVA-hours annually are now available to sell rather than used to power the ESP.

If the outputs of the PowerPlus units reduced to match the kV product of the conventional units so as to produce equivalent ESP collection, the input kVA drops to 131.8 kVA and 1,304,000 kVA-hours per year are available for sale to users.

Table 4

Conventional T/R's

TR #	Conduction. Angle	KV pk	KV min	KV mean	MADC	VAC	AAC	SPM	KV pk x KV mean	kVA in
# 3-1	94	48.96	18.72	33.93	350.9	280	96	82	1661.21	45.60
# 3-2	132	41.76	12.96	28.62	767.1	300	165	23	1195.17	78.38
# 3-3	135	57.6	20.16	41.15	1003	335	165	3	2370.24	78.38
# 3-4	126	57.6	15.84	39.61	971	320	165	0	2281.54	78.38
										280.73

PowerPlus Units- Normal Operation

TR #	Duty Cycle	KV mean	MADC	VAC	AAC	SPM	KV x KV	kVA in	kVA in Sum	KV Prod P+/ kV Prod T/R
# 3-5	56%	47.05	399.5	472	33.5	45	2213.7	27.39	corrected Iac (40.47)	1.33
# 3-6	55%	45.86	337.5	470	27.62	100	2103.14	22.48	49.87	1.27
# 3-7	56%	47.91	400.5	471	29.52	15	2295.37	24.08		1.92
# 3-8	56%	43.86	400	472	29.06	12	1923.7	23.76	47.84	1.61
# 3-9	100%	45.31	933.5	471	59.4	0	2053	48.46	48.46	0.87
# 3-10	100%	45.32	976	470	62.1	0	2053.9	50.55	50.55	0.90
									196.72	

PowerPlus Units- Equivalent Operation

TR #	Duty Cycle	KV mean	MADC	VAC	AAC	SPM	KV x KV	kVA in	kVA in Sum
# 3-5	61%	40.85	247.5	470	20.13	27	1668.72	9.46	
# 3-6	60%	40.76	260	471	19.5	26	1661.38	9.18	18.65
# 3-7	60%	35.09	224.5	472	15.33	15	1231.31	7.24	
# 3-8	60%	34.69	213	471	14.66	15	1203.4	6.90	14.14
#3-9 and # 3-10 Were already operating at 100%								0.00	48.46
								0.00	50.55
									131.79

TVA- JOF

Table 5 displays data obtained from TVA-JOF. A conventional T/R 5AB-1 was removed and replaced with two 56 kW PowerPlus units effectively sectionalizing field 1. Data was obtained from the other inlet fields on ESP's 1-4, and 6 operating at a boiler load similar to ESP 5. This data consistently established that the PowerPlus units put more power into the ESP field while requiring less kVA per kilowatt into the ESP. Based on these readings, for equivalent kW into the ESP, the PowerPlus units would only require 58% to 62% as much kVA as the conventional units. The PowerPlus unit was operating very close to current limit at a low spark rate of 5 to 6 SPM, but it is still not clear from the readings why the kV product for the PowerPlus was not higher than the conventional units. It has not been possible to confirm the accuracy of the kV readings for the conventional units, as they appear somewhat high. This issue deserves further investigation.

In all cases, the PowerPlus unit has demonstrated that more kW can be delivered to the ESP for less input kVA per kW of delivered power. In most cases, the kV product of the output voltage is higher for the PowerPlus unit.

Table 5

Based on readings and measurements made from 6/16/04 t0 6/17/04

DC Mode Data Compared to Other Inlet Fields:

Date	Power Supply	Boiler MW	kVdc	mAdc	kW ESP	Vac in	Vpri	Ipri	Input kVA	kW ESP/ kVAin
6/16/04	4AB-1	90-95	59.5	257	15.29		291	66	31.22	0.49
	5B-1	90	56	733	41.05	473		60	49.15	0.84
	6AB-1	85-90	48	313	15.02		320	65	30.75	0.49
6/17/04	1AB-1	80-90	62	230	14.26		290	55	26.02	0.55
	3AB-1	90-95	58	260	15.08		275	57.5	27.20	0.55
	5B-1	90	57	630	35.91			50	40.96	0.88

Notes:

The PowerPlus unit is designated 5B-1 and uses a DSP controller.

The units designated "x AB" are feeding two fields so therefore he kVdc and mAdc were averaged and the primary current was divided by 2 so as to provide for comparison to a single field.

Readings were taken to compare inlet fields on ESP's with similar boiler MW loading.

For all units 473 Vac was used for input kVA calculations. The actual voltages may have varied slightly.

It was observed that inlet field 5B-1 was operating near current limit while 5B-2 ran at current limit without arcing. This is important to note for sizing P+ units.

Intermittent Energization (IE) Mode:

IE mode is used for high resistivity dust when back corona maybe present. Back corona results when the average current density gets so high that the dust layer, due to its high resistivity, breaks down locally in the areas of highest average current density. Studies indicate that if the peak current can be made higher than the allowed average value for a time not to exceed 2 milliseconds, than the dust layer will then support a peak current density higher than the allowed average value, and more power and higher voltage can be delivered to the field resulting in improved particulate collection.

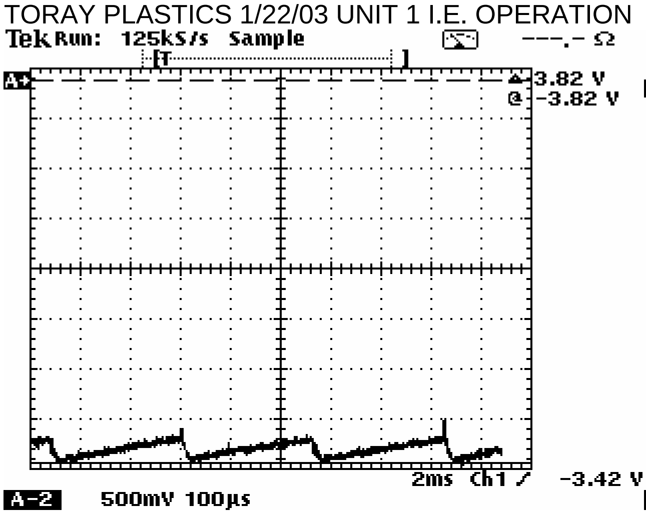
Because of it's high switching frequency and use of Insulated Gate Bipolar Transistors (IGBT's), the PowerPlus unit is able to switch ON and OFF for short periods (in the low millisecond range) while conventional SCR's systems limit the ON-OFF cycle to 25 milliseconds with a resolution of ON time to 8.33 milliseconds. Thus the PowerPlus has a definite advantage over conventional power supplies in IE mode.

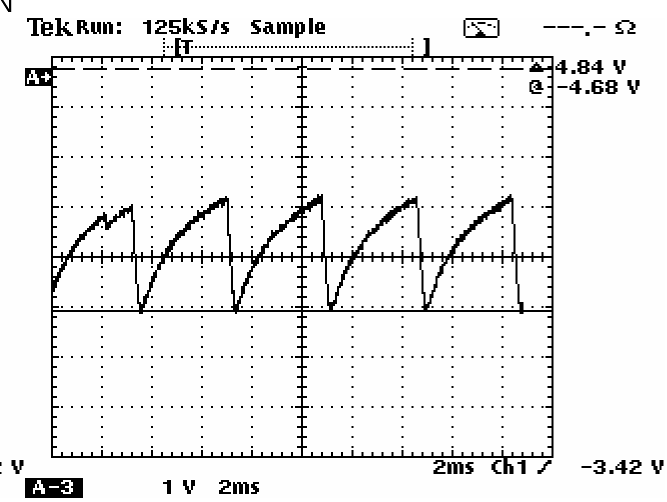
At two sites, observations were made that indicated better performance from PowerPlus units in the IE mode.

Toray Plastics:

This site has a small industrial Wet ESP that sees high space charge due to the very fine particulate produced from a plastic foam manufacturing process. With this load the unit in DC mode was drawing less than 10% of rated mAdc at sparking levels. Below is a snapshot of the unit operating in DC mode versus IE mode. The IE mode yields a higher kV product.

TORAY PLASTICS 1/22/03 UNIT 1 I.E. OPERATION





UNIT #1 D.C. MODE kV (**4kV/DIV**)

kVdc	kV peak	kV product	Mode
29.4	30.7	903	DC

UNIT #1 I.E. .3mS ON 3.3mS OFF (**8kV/DIV**)

kVdc	kV peak	kV product	Mode
26.6	37.4	995	IE
			msec
		0.3	ON
		3.3	msec OFF

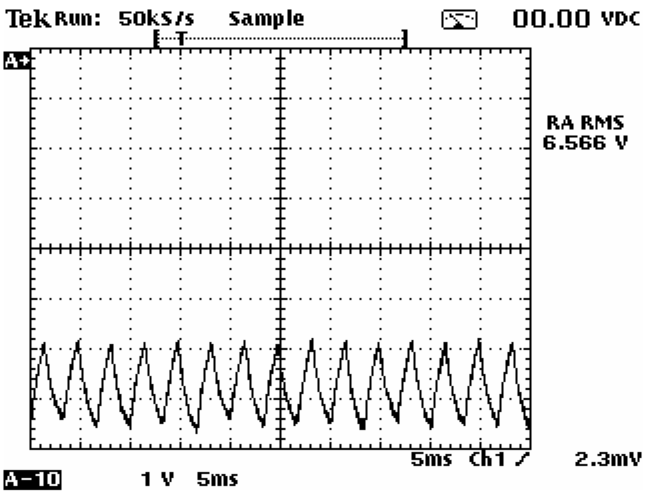
TVA-JOF:

Tests were performed at TVA-JOF to compare IE mode versus DC mode on PowerPlus unit 5B-1. Operating in IE mode, the spark-over level at 5B-1 could be increased with minimal reduction of the kVdc level. This resulted in a higher kV product indicating increased particulate collection.

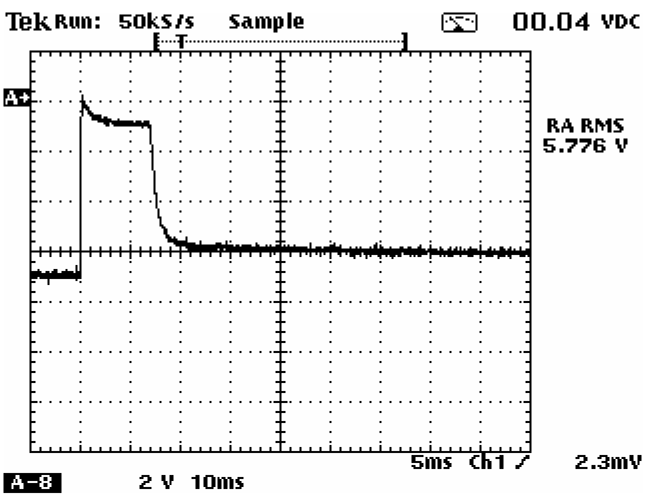
Operation of PowerPlus unit 5B-1:

Time	Mode	spark over kV	kVdc	kVvalley	mAdc	kVproduct	kWesp
700	DC	56.35	56.35	56.35	415	3175	23.39
755	IE	59.4	53.9	47.0	476	3202	25.66
802	DC	55.12	55.12	55.12	502	3038	27.67

IE times were 2.8 milliseconds ON and 1.0 milliseconds OFF (this is a faster rate than can be done with a conventional power supply.



IE Mode:
64.3 kV peaks without arcing



DC Mode:
Response to Arcing
60.4 kV just prior to arc.

These oscilloscope waveforms show that the spark over voltage with IE is running approximately 6.5% higher than in the DC mode. When the unit was switched back to DC mode, the spark over voltage returned to the lower level.

Improved Power Factor:

As can be seen by reviewing the data already presented, the PowerPlus unit typically uses approximately 60% of the kVA required by a conventional unit and still can provide the same kW to the ESP. This is primarily due to the circuit topology (map of how circuit components are connected and function) of the PowerPlus unit. A conventional T/R is single phase and controlled using SCR's in a phase angle adjustment mode of operation. This topology has two characteristics that contribute to requiring more kVA to obtain a given kW to the ESP.

1. Since the output is a single phase rectification of line frequency, there is high ripple on the output voltage. This ripple does not contribute to the kW delivered to the ESP; only the DC components contribute to the kW.
2. With the phase angle control, only part of the incoming 60 Hz source voltage waveform is utilized. Yet the current taken from the source is still the secondary rms current times the turns ratio of the transformer. If the ESP is requiring full mAdc at ½ of rated voltage, the input kVA from the source will still be at its full rated value.

Conversely, the PowerPlus unit produces a near DC output so there is very little wasted ripple. All of the output waveform produces kW into the ESP. Additionally, the incoming AC source voltage is rectified and filtered into a DC bus voltage right at the input to the PowerPlus unit. This input rectifier and filter combination averages the high frequency pulses resulting in the input kVA being proportional to the kW required by the ESP. The result is that at 50% rated kVdc and full rated mAdc, the PowerPlus will require only slightly more than 50% of rated kVA from the source. A conventional T/R power supply will draw full kVA at 50% kVdc..

To dramatically see the difference in required kVA between a conventional T/R and a PowerPlus unit, consider the case of a hypothetical shorted field. The conventional unit, power supply will draw full rated kVA while running at current limit. The PowerPlus unit under the same condition will draw approximately roughly 5AAC, less than 5kVA.

DSP Controller with Fast Response (Available in 2005)

Since the PowerPlus unit uses IGBT's and operates at high frequency, it can sense an arc and shut down in as little as 30 microseconds. No follow-up energy from the source is dumped into the arc, and the current surge from the source is insignificant. Conventional T/R units typically see surges of 2.5 to 3 times rated current on arc over. This causes distortion on the AC feeder system and produces greater wear and tear on circuit breakers and contactors.

The DSP (digital signal processor) can sample analog signals very quickly. The kVdc is sampled approximately every 33 microseconds. Since the IGBT's can be adjusted very quickly, the PowerPlus unit can now adapt rapidly to changing conditions. Through the use of fast sampling of the kVdc signal, the DSP can make decisions that allow for self tuning algorithms to be implemented.

1. Coming out of a Quench Period, the unit will go to 100% current and ramp on as fast as possible to charge the ESP back to voltage. The unit then transitions to a slow ramp to maintain the desired spark per minute setting once the setback voltage level is sampled. With its fast recovery ramp, the PowerPlus spends more time at higher kVdc levels than a conventional SCR-T/R system.
2. The combined speed of the IGBT's and DSP allows for the PowerPlus unit to have an ON time as low as 0.1 milliseconds and an OFF time as short as 1.0 millisecond. Wave shaping is performed by selecting the kV peak and kV valley of the output voltage waveform. These fast times provide better ability to manage back corona conditions than with a conventional T/R unit.
3. The DSP controller offers self tuning algorithms that continually progress towards minimum quench and voltage setback levels while maintaining a user selected spark per minute setting.
4. Software for the DSP will include an auto selection algorithm that determines whether to run in IE mode or DC mode for best performance.

Installation Advantages of PowerPlus:

Table 6 on page 15 provides a comparison of the PowerPlus unit rated 70 kW, 70 kVdc with a conventional SCR-CLR-T/R system rated for 60 kW, 60kVdc. Some points to note:

1. **Factory Wired-** The PowerPlus is an integrated factory wired and tested component versus the three conventional components (SCR + CLR + T/R) that have to be wired together in the field.
2. **Smaller Size-** The PowerPlus takes is 40% of the volume, less than 50% of the foot print floor plan, and less than 20% of the weight of a conventional unit. It can be more closely mated to the HV electrode connection thus reducing duct work. The smaller footprint of the PowerPlus unit leaves more open space on the ESP roof providing better accessibility for all equipment located on the roof.
3. **Less Input Wiring-** The PowerPlus is a three phase system with a higher power factor compared to the single phase conventional system. The input circuit breaker for the PowerPlus will be rated 150 AAC while the conventional system requires a two pole breaker rated 250 to 300 AAC. The power wiring to the PowerPlus must carry 100 AAC while the wiring for the conventional must be rated for 200 AAC.
4. **Less Control Wiring-** The Power Plus only needs 5 wires for control and one for communications, each in their own conduit. The conventional solution requires 9 to 11 control wires, 2 twisted shielded feedback cables, and one communications cable, each in their own conduit.

5. **Less Dielectric Fluid-** The PowerPlus contains less than 25% of the dielectric fluid of a conventional T/R tank. In the event of a leak this reduced volume presents less safety and environmental issues. The optional drip pan is also smaller so disposal of any collected water is easier. Another important point pertaining to the insulating fluid is that the circuit topology of the PowerPlus results in greatly reduced energy per cycle delivered to the HV tank portion of the power supply making it more difficult to ignite the fluid in the event of a fault condition. If the optional Dow Corning 561 silicone fluid is used the resistance to ignition is even greater.
6. **Remote Control Flexibility-** The PowerPlus, can be locally controlled using the handheld NWL Graphic Voltage Controller (GVC) display module. This device requires 15VA of 120V power and has no fan or filters. Multiples of this displays can be mounted in a control enclosure the size of a single SCR controller with a cable running from each PowerPlus back to it's display. Optionally, a single display can function in a network mode and monitor up to 15 units, with all the PowerPlus units connected on one RS-485 communications line. With either option the floor space, volume, and cooling required in a control room are greatly reduced.

Table 6

PARAMETER	POWERPLUS 70	CONVENTIONAL T/R SYSTEM
kVdc	70	60
mAdc	1000	1000
Output kW	70	60
Peak kV (Open Circuit)	77 (point at which OV trips)	100.8
% Ripple kVp-p	3-5	35-45
Input Vac	480	480
Number of phases	3	1
Iline (AAC)	94	186
Losses (kW)	3.6	3.3
Power Factor	.94	.63
Input kVA (Iff = 1.2)	78.3	89.3
Operating frequency	25 kHz	60 Hz
EMI filter	Yes	No
Arc shutdown time	30 usec	8.33 msec
Cooling	Forced Air (1/2 HP fan)	Natural Convection
Max. 24 hr. Ambient Temp. (deg C) (Max = 50 deg C for 4 hr.)	40	40
System Volume envelope (cubic feet)	24.8	65
System Plan envelope (square feet)	9.9	21
System Weight (lb.)	700	3750
Gallons of fluid	29	125
Wiring from T/R to control	Factory	Field
System Components	Integrated PowerPlus Unit	• T/R • CLR • SCR Controller
Number of HV Connections	1	1
Number of Power Cables	3 to PowerPlus (100A)	• 2 source to controller • 1 controller to CLR • 1 CLR to T/R • 1 controller to T/R (all 200A)
Number of Control Wires	• 3 for Enable/ HV ON • 2 for Master Fuel Trip interlock	• 3 for Enable/ HV ON • 2 for Master Fuel Trip interlock • 4 to 6 for T/R liquid level and temperature alarms
Number of Communications Cables	1 three wire shielded RS- 485 cable	1 three wire shielded RS- 485 cable
Number of Feedback Cables	None	2 twisted shielded pairs for kV and mA from T/R to controller

Packaged for Corrosive Environment:

For corrosive and acidic plant environments the following upgrades are available-

1. The HV tank, radiators, the enclosure, and the ground disconnect switch box are fabricated from 316L Stainless Steel. Additionally, a finish coat of ASA 61 gray enamel will be applied to aid in heat dissipation.

2. All hardware is 316L Stainless Steel.

3. The IGBT heat-sinks have the fins coated with a matte tin finish which is superior to the standard "Aavgard" finish in acidic environments.

Product Reliability Enhancements

A major user concern with an advanced technology product is reliability. Since the introduction of PowerPlus in 1999, NWL has aggressively worked to improve the reliability of the PowerPlus unit. NWL performed extensive in-house testing on this product including numerous thermal tests at ambient temperatures up to 50 degrees C, high rate extended arcing tests, outdoor continuous arcing load operation for several months at a time, and certification tests for UL/CSA and CE mark. Additionally, every product shipped to the field was subjected to a final test procedure that includes high voltage open circuit testing, load testing, load testing with arcing, and short circuit operation. The nearly 5 years of field operating experience has led to further improvements to improve product reliability under a variety of operating conditions. Table 7 summarizes the field problems encountered and the resulting improvements made to the product.

Table 7

Field Problem	Improvements Implemented
Shorting of HV Rectifier stages	• Use of proprietary winding techniques to eliminate use of ceramic balancing capacitors that were failing after several months of operation. • Additional blocking diode stage added at a site where extensive circulating current was observed during arc over (now a standard feature on all new units). • Increased output resistance from 12 ohms to 75 ohms.
Input MOV's Failing	• Determined that power source and ESP must be connected to the same ground grid. If the source and ESP are connected to different grids, the IGBT's and/or MOV's see severe transient voltages, especially on arc – over. • Ungrounded the neutral point of a wye connected MOV network so that they would not be exposed to over voltage if one leg of an ungrounded delta system suddenly became grounded. •

Shorting of Input Bridge Rectifier	• Problem with voltage transients being more severe on ungrounded delta systems. Replaced wye connected MOV network with snubber pc board assembly placing an MOV-R-C network across each diode device in the three phase bridge • On a few occasions, the filter choke between the rectifier and DC bus caps arced to the core taking out the input rectifier. Replaced filter choke with a balanced two coil design that eliminated the arc over to the core and balanced both halves of the DC bus capacitors above ground.
Shorted IGBT Modules	• Implemented use of improved thermal pad to better accommodate flatness tolerance issue between the IGBT module and heat-sink • ESD workstation setup for handling of IGBT modules prior to protection circuit being installed at gate and emitter leads • Added grounding strap from heat-sink to enclosure frame. • Floated resonant capacitor assembly to minimize stray capacitance from resonant capacitors to ground. • Added semiconductor fuses to AC lines to minimize fault propagation in the event of a semiconductor failure
Excessive Over Voltage Trip Alarms	• Modified software to implement digital filtering to minimize false over voltage sensing. • Added Schottky diode to clamp negative going spikes at the input to the over voltage comparator that occur at some sites during arcing events.
Control Board Resets and Other Erratic Operation	• Determined that a number of battery-backed RAM ICs were counterfeit. Identified counterfeit ICs and replaced them with the proper devices. • Some Analog Devices watchdog ICs were prone to resets on arc over, especially on wet ESP's. Replaced ICs with Maxim watchdog ICs with superior noise rejection.

Summary:

The PowerPlus can provide kVdc outputs that range from fast IE (low to fractional ON and OFF times) to nearly pure DC as well as numerous operational modes in between these two limits. This provides maximum flexibility in obtaining optimum ash collection from various fossil fuels.

With its high power factor, the PowerPlus unit provides much more kW into the ESP while requiring less kVA from the source when compared to conventional units.

The reduced size and weight and less dielectric fluid of the PowerPlus allows for easier installation and service, less fire and environmental hazard, less field wiring costs, and lower total installed costs.

The PowerPlus represents the future of power supply technology for ESP’s, and will soon be the standard solution for powering ESP fields. Any user considering upgrades to ESP’s should be fully well aware of PowerPlus technology and its potential for enhancing ESP performance.