Shedding Light on the Operational Differences of 3 Phase Transformer Rectifiers and Switch Mode Power Supplies

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Abstract:
The purpose of this paper is to eliminate confusion and misinformation regarding the operational differences of a 3 phase SCR controlled transformer rectifier (3 phase SCR-TR) and the NWL PowerPlus™ switch mode power supply (SMPS) when operating on an actual electrostatic precipitator (ESP). In brief, SMPS electrical performance across all fields is quite consistent while 3 phase-SCR-TR electrical performance is strongly dependent on the operating point for each field.

Analyzing actual ESP operating data across all fields from inlet to outlet, this paper will present a realistic comparison of the electrical parameters for equivalent rated SMPS versus 3 phase SCR-TR operation.

The collected ESP data consists of the kVdc and mAdc for each field on an operating ESP presently using SMPS units. The evaluation then compares input kVA, power factor, harmonic current distortion levels, and kVpeak to kVdc ripple for both SMPS units and 3 phase SCR-TR units for each field. The net kVA, power factor, harmonic current level, and kW for the entire ESP box will also be compared.

The purpose of this paper is to educate users and OEMs on the electrical performance differences for each technology over the realistic spectrum of actual operational conditions on an ESP.

Introduction:

Switchmode power supplies (SMPS) utilize fast switching topologies and devices such as IGBTs to reduce size and weight of a power supply. Additionally, SMPS provide better power factor, lower ripple, and quicker response over a wide range of operating conditions [1], [2].

In ESP applications, the low ripple aspect of the SMPS enables the output kVdc to operate closer to the peak kV so as to provide improved collection over the traditional single phase SCR-CLR-TR set solution [3].

Efforts to reduce the power supply cost have resulted in ESP sites where three phase SCR-CLR-TR set solutions have been used. While the three phase SCR-CLR-TR set has more of a pure DC (less ripple) than the traditional single phase SCR-CLR-TR set, it only approaches the low ripple and power quality performance of a SMPS when the operating point is quite close to rated kVdc at rated mAdc.

The inherent problem with the three phase SCR-CLR-TR solution is that in reducing the kV output below rated output, the SCR (thyristor) has to be "phased back" from the zero crossing of the applied voltage. This increased delay angle increases kVA demand from the source (lower power factor), output voltage ripple and input line current harmonic levels [4], [5].

This paper will review fundamental theoretical performance for SMPS versus three phase SCR-CLR-TR using SMPS data collected from an actual ESP. Combining this site data with SMPS and three phase SCR-CLR-TR data collected at NWL, the paper will then compare ESP and feeder system electrical performance for SMPS versus three phase SCR-CLR-TR solutions

Fundamental Overview 3 Phase SCR-CLR-TR:

Reference [4] covers the fundamental equations describing the performance of a three phase delta/wye transformer connected to a three phase full wave diode bridge controlled form the primary side by in-line anti-parallel connected thyristors (AC switch).

All of the equations relate performance such as DC output voltage, line currents (and their harmonics), and the output kW to input kVA ratio to the delay angle (α). At maximum SCR conduction, alpha is zero. As the gating of the SCR is delayed, alpha increases. There are three modes of operation that occur as alpha increases.

For this paper, only the first two modes matter. If the 3 phase TR is operating in mode 3, its electrical performance will be very poor. (kVdc would be less than 38 kVdc on a 70kVdc rated unit).

Mode 1 for $0 < \alpha <= 60$ degrees:

$$Ud = Udo\,((1 + \cos\alpha)/2)$$

Where Ud is operating kV and Udo is the maximum light load value of kV (approximately 77kVdc for a unit rated 70 kVdc at full load). α is in radians

$$F = 3(1 + \cos\alpha)/(2\pi \sqrt{\left(1 - \frac{3\alpha}{4\pi}\right)}\,)$$

Where F is ratio of kWout/kVA_in and α is in radians

Mode 2 for $60.1 < \alpha < 90$ degrees:

$$Ud = \sqrt{3}\ Udo\,(\sin(\alpha + \pi/3))/2$$

Where Ud is operating kV and Udo is the maximum light load value of kV (approximately 77kVdc for a unit rated 70 kVdc at full load). α is in radians

$$F = 3\,(\sin(\alpha + \pi/3))/\pi$$

Where F is ratio of kWout/kVA_in and α is in radians

From a practical perspective, what these equations mean is that as the delay angle is increased (firing of the SCR relative to its zero crossing of the synchronization phase is delayed), a number of electrical performance variables change in an undesirable manner.

1. The output voltage (kVdc) decreases. This leads to increased ripple. As the kVpeak increasingly gets larger than the kVdc level, dust collection decreases.
2. F (kW_out/kVA_in) decreases meaning more kVa input from the source is required to supply the required output kW level. In short, power factor decreases.
3. The increased kVA required means higher line currents and thus, more amperes of higher order harmonics (5th, 7th, 11th, 13th, etc).

Regarding the increase of Output voltage ripple as the delay angle, α, is increased, refer to the following figure [5].

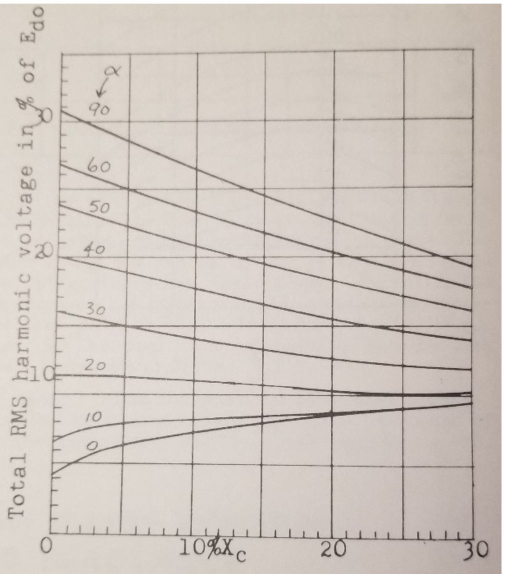

Figure 1: This curve show rms ripple versus commutating reactance (about 15% for 3 phase TR) as a function of delay angle α(Edo about 77 kV)

The kV peak to kV average is 1.414 times the rms value. As the delay angle is increased from 0 to 90degrees, the ripple increases approximatley 3 times above the value at full conduction (α = 0).

Factory Testing: SMPS v. 3 Phase SCR-CLR-TR:

To further confirm the basic theory regarding operation of a three phase TR, NWL tested both a 70kVdc, 1000 mAdc PowerPlus and a SCR controller and three phase CLR-TR tank rated 70kVdc at 1000 mAdc. Total reactance of the three phase SCR-CLR_TR set was approximately 30%.

The load consisted of various resistor combinations in parallel with a 140 nF capacitor array. Both units were operated approximately 65kVdc with the resistive component of the load varied to draw output currents of 10%, 25%, 50%, 75%, and 100% of rated mAdc. Additionally the load was adjusted to draw rated mAdc at approximately 36 kVdc and 54 kVdc.

Figure 2: Contoller and HV tank for 3 phase SCR-CLR-TR system with approximatley 30% system reactance. Rated 70kVdc at 1000 mAdc.

Figure 3: PowerPlus SMPS rated 70 kVdc at 1000 mAdc. (50 kHz resonant)

Using the data collected, the following curves were developed to provide relative performance of the two power supplies when connected to the ESP field. All of the following graphs are based on holding rated mAdc while phasing back (increasing the delay angle) the SCRs for each kW output level.

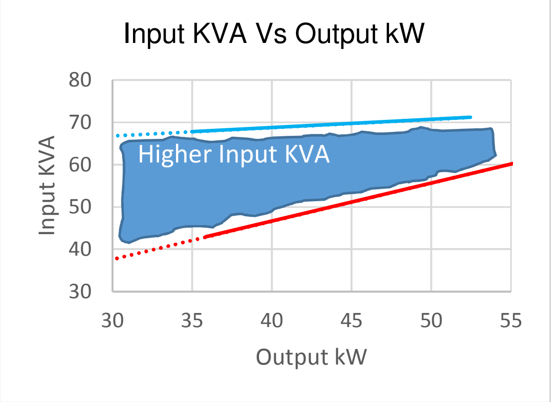

Figure 4: Input kVA versus kW ouptut to ESP. Red is PowerPlus, Blue is 3 phase TR

This graph emphasizes that the 3 phase TR, as its SCR line switches are phased back, needs increasingly more kVA relative to the kVA used by the PowerPlus. This is a direct result of portions of the incoming sinusoidal source voltage not being effectively utilized due to the increased delay angle. For ESP fields operating at high mAdc levels and more than 7 to 8% below the rated kVdc of the 3 phase TR, the kVA required from the source remains high even though the kW to the ESP is reduced.

A SMPS unit such as the PowerPlus always draws input kVA at a high power factor in providing the kW output to the ESP. Over the normal range of ESP operation, the ratio of kVA needed by the PowerPlus compared to the kW delivered to the ESP remains relatively constant.

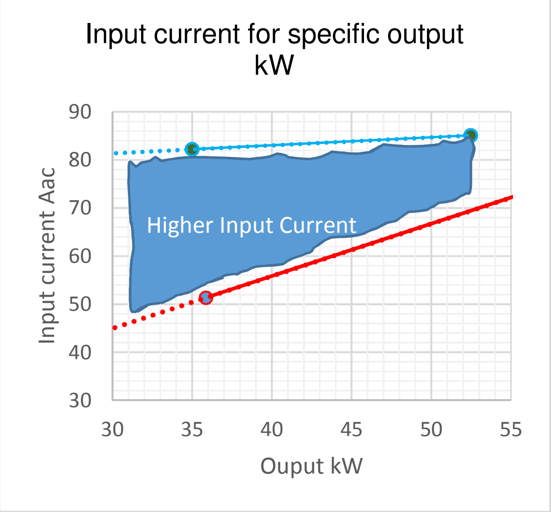

Figure 5: Input Line Current versus kW output to ESP. Red is PowerPlus, Blue is 3 phase TR.

This graph illustrates that the line currents for the three phase TR follow the same trend as the kVA does in Figure 4. This lower power factor and resulting higher line currents for the 3 phase TR at kVdc levels below rated kVdc lead to increased losses in the ESP facilities' feeder system for the ESP.

The case of comparing the input line current for supplying rated mAdc into a dead short (such as occurs during an arc) dramatically points out the shortcoming of the SCR based 3 phase TR versus the IGBT based PowerPlus. When a 3 phase TR is phased controlled to maintain rated mAdc, rated primary current is drawn from the source (Rated kVA and Aac are needed to provide essentially "0" kW to the load). For the PowerPlus providing rated mAdc into a short, only approximately 5 Aac are drawn from the source.

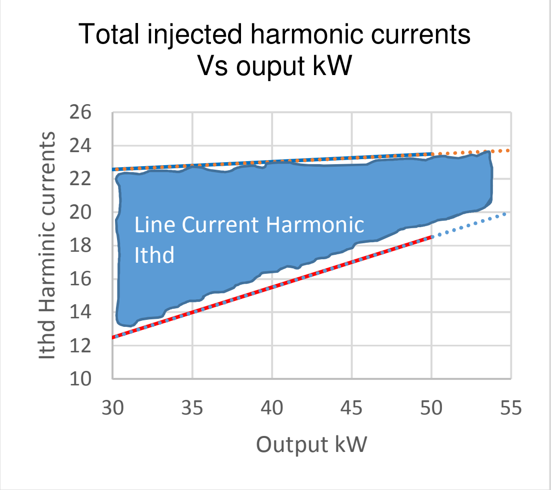

Figure 6: Harmonic Current Ithd at Input versus Output kW. Red is PowerPlus, Blue is 3 phase TR

Due to the high power supply reactance (around 30%) and when operating at a low delay angle, the Ithd **percentage** for the 3 phase TR is lower than for the PowerPlus. It is, however, important to point out that with the increased kVA demands of the 3 phase TR (Figure 4), that the **actual Ithd amperes** run somewhat higher than for the PowerPlus unit. As the delay angle increases, this higher Ithd ampere level of the three phase TR increases even more above the Ithd ampere level of the PowerPlus.

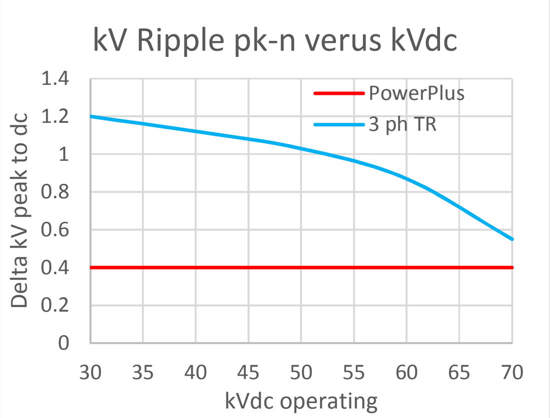

Figure 7: Ripple: kVpeak to kVdc value versus operating voltage (Cload = 140 nF; Rload varied to keep Id in the 80 to 100% range for each kVdc test point)

While the ripple for the 3 phase TR can be as much as 3 times that of the PowerPlus, for normal ESP operation, this ripple difference only results in a 1 to 1.5% difference in the kV product (kVdc multiplied by kVpeak) that is indicative of migration velocity for the ESP [3]. With so many factors affecting ESP performance, this is most likely not a serious issue.

SMPS data collected on a real ESP:

Electrical data was collected from an ESP that has 30 PowerPlus units rated 70kVdc at 1000 mAdc and 6 units rated 70 kVdc at 1500 mAdc. This paper is primarily focused on the impact of 3 phase TR on the ESP electrical system of the ESP box as the output kVdc of the 3 phase TR is phased back. Therefore, fields operating at under 10kW into the field were not evaluated. The data collected and evaluated is shown below in Table 1.

ESP Unit 3 Operating at 790 MW:
PowerPlus collected data:

P+	Vac	Aac	kVdc	mAdc	kWout
3A11	459	39	46	454	20.8
3A12	474	35	45	548	24.6
3A13	464	51	48	670	32.1
3A14	478	62	46	898	41.3
3A15	459	114	54	1529	82.5
3A3	468	68	45	814	36.6
3A4	457	81	54	1009	54.4
3A5	471	74	47	1015	47.7
3A6	454	114	55	1525	83.8
3A7	474	110	53	1529	81.0
3A8E	456	79	51	986	50.2
3A8W	456	86	57	1024	58.3
A16E	470	84	58	1023	59.3
3B14	467	48	48	623	29.9
3B15	475	102	55	1339	73.6
3B2	501	34	49	387	19.0
3B3	456	29	39	322	12.5
3B4	473	62	49	787	38.5
3B5	458	63	51	806	41.1
3B6	477	104	54	1527	83.6
3B7	459	110	53	1522	80.6
3B8E	473	86	53	1021	54.1
3B8W	473	84	51	1023	52.1
B16E	455	62	52	775	40.3
B16W	452	86	58	993	57.5

Table 1: PowerPlus data collected from actual ESP

Calculating the kVA input from the above site data and applying the Ithd results from factory testing, the PowerPlus performance is further evaluated.

The P/S column is the ratio of kW to the ESP field divided by the input kVA from the source. This number is effectively the output kW into the field divided by the product of efficiency multiplied by power factor.

PowerPlus Calculated Data from Site Data:

P+	kVA_in	P/S	I_line	Ithd
3A11	31.0	0.67	39.0	10.3
3A12	28.7	0.86	35.0	11.5
3A13	40.9	0.78	51.0	13.9
3A14	51.3	0.81	62.0	16.8
3A15	90.5	0.91	114.0	30.0
3A3	55.1	0.66	68.0	15.3
3A4	64.0	0.85	81.0	21.0
3A5	60.3	0.79	74.0	18.9
3A6	89.5	0.94	114.0	30.4
3A7	90.2	0.90	110.0	29.5
3A8E	62.3	0.81	79.0	19.7
3A8W	67.8	0.86	86.0	22.3
A16E	68.3	0.87	84.0	22.6
3B14	38.8	0.77	48.0	13.2
3B15	83.8	0.88	102.0	27.2
3B2	29.5	0.64	34.0	9.7
3B3	22.9	0.55	29.0	7.6
3B4	50.7	0.76	62.0	16.0
3B5	49.9	0.82	63.0	16.8
3B6	85.8	0.97	104.0	30.4
3B7	87.3	0.92	110.0	29.4
3B8E	70.4	0.77	86.0	20.9
3B8W	68.7	0.76	84.0	20.3
B16E	48.8	0.83	62.0	16.5
B16W	67.2	0.86	86.0	22.0

Table 2: Additional PowerPlus parameters calculated from actual ESP site data

To evaluate 3 phase TR performance on the same ESP as the SMPS, the chapter 4, section 4 of reference [4] was confirmed by comparison against factory testing data of the 3 phase TR done at NWL. The combination of the equations from reference [4] and the factory test results were then applied to account for the 3 phase TR operating at both lower kVdc levels and lower mAdc levels.

3 Phase TR Projected Data from factory testing and reference equations:

T/R	kVA_in	P/S	I_line	Ithd
3A11	34.3	0.61	43.1	10.1
3A12	41.8	0.59	51.0	12.1
3A13	49.8	0.64	62.0	14.9
3A14	68.0	0.61	82.2	20.1
3A15	110.3	0.75	138.8	36.8
3A3	62.2	0.59	76.8	18.6
3A4	72.8	0.75	91.9	23.1
3A5	76.2	0.63	93.4	23.2
3A6	109.7	0.76	139.5	37.0
3A7	110.8	0.73	134.9	35.6
3A8E	72.0	0.70	91.1	22.7
3A8W	73.4	0.79	92.9	23.5
A16E	73.3	0.81	90.0	22.8
3B14	46.4	0.64	57.4	13.7
3B15	96.4	0.76	117.1	30.5
3B2	28.7	0.66	33.1	7.7
3B3	26.8	0.47	33.9	7.8
3B4	58.1	0.66	71.0	17.3
3B5	58.9	0.70	74.3	18.2
3B6	111.8	0.75	135.3	35.9
3B7	110.2	0.73	138.6	36.6
3B8E	74.0	0.73	90.3	22.7
3B8W	74.7	0.70	91.2	22.8
B16E	56.4	0.71	71.6	17.5
B16W	71.1	0.81	90.8	22.9

Table 3: Projected 3 phase TR parameters for providing each ESP field with same kVdc and mAdc as PowerPlus.

ESP Feeder Electrical Performance for SMPS v. Three Phase SCR-CLR-TR:

From the reference point of the feeder transformer that provides power to the HV power supplies on the ESP roof, the key parameters to provide a specific kW level into the ESP box are kVA, line current magnitude, and level of harmonics in the line current.

Parameter	PowerPlus	3 ph TR	Units
kW into ESP	1255.4	1255.4	kW
kVA from feeder	1503.9	1768.1	kVA
Feeder current	1847.5	2172.0	Arms
Feeder Ithd level	492.5	554.1	Arms

Table 4: Comparison of utility feeder electrical parameters for comparing PowerPlus versus 3 phase TR.

The biggest advantage to the utility when comparing the PowerPlus to the 3 phase TR is the additional revenue production from the reduced feeder kVA of 264.2 that the PowerPlus provides. This KVA is no longer needed to power the ESP and becomes available to the grid to be sold as kW-hr.

delta kVA	264.1
PF at consumer	0.9
utilization	0.7
kwHr/day	3,994
kWhr/yr	1,437,739
$/kw-hr	$0.05
$ per year	$71,887
10 yr	$718,870

Table 5:Potential kW-Hr revenue from feeder kVA saved using PowerPlus.

The lower feeder current required by each PowerPlus unit results in lower losses and costs related to the feeder transformer and cables for providing current to the HV power supplies on the ESP roof. With the lower losses, the feeder transformer and cables run cooler than they would with the 3 phase TR solution. This equates to longer life for the feeder transformer and associated cables.

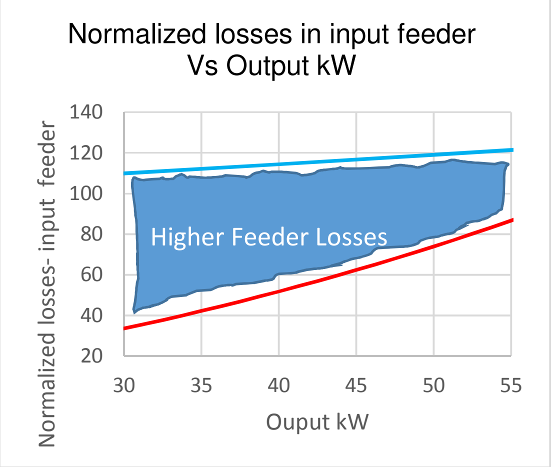

Figure 8: For example ESP site, relative increased feeder losses associate with using 3 phase TR providing same kW into ESP as PowerPlus.

Conclusions:

This paper has used data from an existing ESP site to establish that a 3 phase TR solution operating at the same kVdc and mAdc as the existing PowerPlus solution would require 20% more kVA from the utility feeder system. This additional kVA along with its associated higher currents causes higher losses and shortens the life of the feeder system components. Using the 3 phase TR solution also results in diminished availability of generator kVA to be sent to the grid for sale at the consumer end as kW-hr revenue.

There is no doubt that when the kVdc required at the ESP field is close to the rated kVdc of the HV power supply (greater than 65 kVdc for a unit rated 70kVdc (at full mAdc output)) that the 3 phase TR solution approaches the performance of the PowerPlus solution (within 5%). It is also true that due to the inherent limitations of an SCR controlled solution that the 3 phase TR solution performance deteriorates at an increasing magnitude as the kVdc level is further reduced below the rated output kVdc.

For the utility user that wants continued high ESP performance while allowing for fuel flexibility, wider range of the process variables affecting particulate properties, and aging of the ESP internals, the PowerPlus unit will continue to meet this high performance level over a much wider range of load conditions than the 3 phase TR unit.

References

[1] Erickson R.W., Maksimovic D., Fundamentals of Power electronics, 2d ed.,2001, pp 615-617, pp. 740-746.

[2] Paice, D.A., Power Electronic Converter Harmonics, 1995, pp. 99-103.

[3] White, H.J., Industrial Electrostatic Precipitation, 1963, pp. 198-202.

[4] Rombaut C., Seguier G., Bausiere R., Power Electronic Converters: AC/Ac Conversion (Volume 2), 1987, pp. 171-186.

[5] Stevenson A.C., Power Converter Handbook, 2002, (General Electric Canada), pp. 121-123.