Intermittent Energization with High Voltage Switchmode Power Supplies

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Summary / Abstract:

Numerous articles and industry reports have documented the collection improvements obtained by DC mode operation of switchmode HV power supplies when compared with conventional TR-thyristor systems. Several articles have reported that improved intermittent energization (IE) of the ESP field can be obtained using a switchmode HV power supply. The focus of this paper is to examine the operation of switchmode HV power supplies in IE mode. The paper will review electrical operation of IE in conventional TR systems compared to switchmode units, discuss user experience at a site utilizing IE mode and present the electrical performance of the ESP field in IE mode.

Introduction

White [1] covered the basis for back corona and benefits attributable to intermittent energization (IE) of the precipitator field. In recent years, Reyes [2] and Klippel (and others) [3] established that switchmode power supplies in IE mode provide up to 20 to 30% improvement over conventional thyristor-transformer-rectifier (TR) solutions operating in IE mode.

This paper will examine the electrical IE performance of a conventional solution versus the switchmode power supply, review data and user feedback from a site with switchmode power supplies operating in IE mode, and then explore means to optimize the switchmode-precipitator system for IE mode of operation.

IE Mode of Operation:

As the resistivity of the particulate in the dust layer increases, the electric field in the dust layer increases with increase in the current density. At some level the electric field is high enough to break down the dust layer forming pockets of back corona. With increasing current density, back corona increases and precipitator collection efficiency decreases.

The dust layer also forms a capacitance in parallel with the resistance of the dust layer due to the dielectric constant of the particulate. The time constant for the dust layer is then

$$\tau = \varepsilon_r * \varepsilon_o * \rho \quad (1)$$

Where ρ is the resistivity, ε_o is 8.85e-12 farads/meter, and ε_r is the relative dielectric constant of the particulate.

Nichols[4], in a report prepared for EPRI and NWL, stated that the decay time for ESP field is between 15 and 20 milliseconds with the decay time for the dust layer being dependent on the resistivity of the dust layer and the dielectric constant of the dust. For dust resistivity of 1e+10, 1e+11, and 1e+12, the time constants for the dust layer are typically 2.7, 26.7, and 266.7 milliseconds.

As the resistivity of the dust increases, the time constant of the dust layer also increases. Since the breakdown of the dust layer leading to back corona primarily is a function of the average voltage, a fast rising current charging the dust layer allows higher kV levels and higher current density. As long as the response of the control of the power supply is sufficiently fast and precise and the average milliamp value is not too high, back corona is inhibited. It is this relationship that forms the basis of IE operation which allows for increased precipitator efficiency.

IE Control of Power Supplies:

The conventional thyristor- TR system is phase –controlled voltage source feeding a current limiting reactor (inductor) that is then matched and rectified for connection to the ESP field, which is essentially a RC load.

Because the thyristors must be synchronised with the incoming line frequency, the ON time is limited to multiples of one-half cycle and the OFF time then needs to be multiple full cycles of the line frequency so as to not saturate the high voltage transformer.

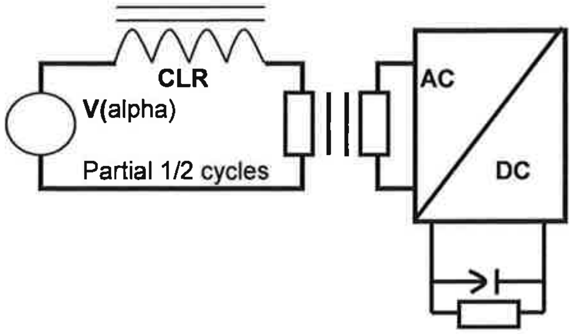

Fig. 01: Simplified model of TR-thyristor system

Thyristors turn on when gated, but turn off only when the current through the device goes to zero. The result is complex waveforms that depend not only on the control command, but also on the value of the circuit components and the operating conditions of the circuit.

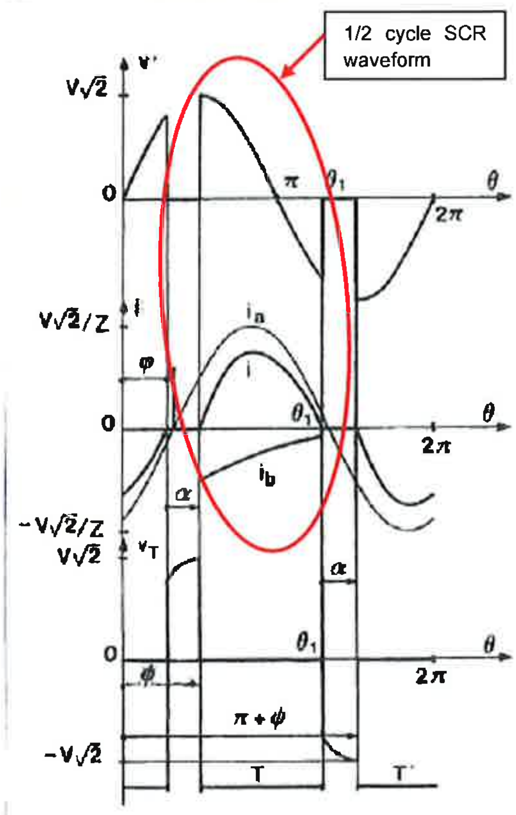

Fig. 02: Typical SCR waveform for complex load [5]

Numerous switchmode power supplies, such as the PowerPlus, function as a current source over a wide range of typical load conditions. This topology provides for a more basic circuit model.

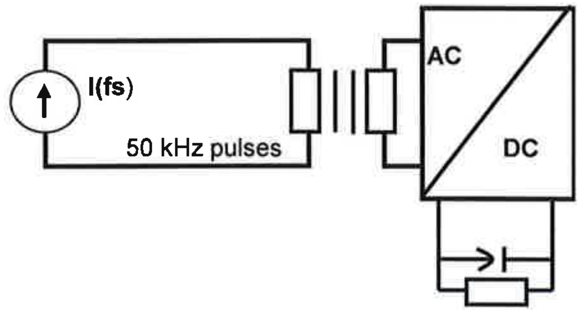

Fig. 03: Simplified model of Switchmode power supply

Since the switchmode power supplies are controlled with IGBTs, both the turn-on and the turn-off of the device are controlled by the gating circuit. Combined with the high frequency switching, the control of voltages and currents can be very precise. The fact that the power supply works as a current source means that the charging of the ESP field (which looks like a capacitor at high frequency) is quite linear. In IE mode, this simplifies the control strategy when compared to the complex waveforms generated by the thyristor system.

Pspice simulations were run to compare IE operation of the thyristor- TR system to IE operation of the switchmode power supply. Some typical ON and OFF times from a site that will be reviewed in the next section were used. A 55kVdc, 1000 mAdc (50% total reactance) conventional system was compared to a switchmode power supply rated 70 kW, 70 kVdc. In both cases a simplified load of 100 nF was in parallel with a series network of 60 k-ohm connected to a zener diode used to create an effective corona onset voltage of 20kV.

No attempt was made to match the load to the various ON and OFF settings. The intent was to compare the control of the thryristor system with that of the switchmode system. The switch mode ON and OFF times were set in millisecond units. The ON and OFF times for the thyristor system were set as follows:

1. The ON time was set as ½ cycle of line frequency. The firing delay

angle (FDA) was then estimated to match the ON time of the switchmode unit. In some cases, this setting produced lower than expected results and others, higher than expected results. The cause of this variation is that the extinction angle (point at which the thyristor current goes to zero) was not accounted for.

2. The OFF time was set as multiples of a full cycle of line frequency.

Pspice Switchmode Results:

ON time (msec)	OFF time (msec)	kV peak	kV valley	kVdc
2.3	37.1	38.7	20.1	23.3
3.5	25.0	45.2	20.1	26.1
4.5	37.1	49.3	20.1	25.9

Table-01: Simulation Results for the Switchmode power supply

Pspice Thyristor-TR Results:

ON time FDA (degrees)	OFF time (# of cycles)	kV peak	kV valley	kVdc
130	2	30.0	20.1	21.5
130	3	30.0	20.1	21.0
105	1	49.1	21.0	29.3
105	2	49.2	20.1	25.3
83	2	68.1	20.1	29.1
83	3	68.1	20.1	25.7

Table-02: Simulation Results for the Thyristor-TR system

For Tables 01 and 02, matching colors correspond to similar ON and OFF times. Because the OFF times for the conventional thryistor-TR system are limited to full cycle multiples of the line frequency, both a shorter OFF time and a longer OFF time than was used for the switchmode units is presented.

In reviewing the results of the Pspice simulation, it became evident that the thyristor controller, for ON times of approximately 3 to 8 milliseconds, with the proper ramp and feedback control could adjust the firing delay angle (FDA) to achieve the appropriate ramp up of the kV during the ON time period.

The issue with a large firing delay angle and a small ON time (especially for times less than 3 milliseconds) is that the peak of the sine wave at time of gating is at a point of rapid decline in magnitude. The result is that there is not sufficient voltage remaining to then charge the capacitance of the ESP field to the required kV peak level.

The major issue with the thyristor controller is the large discrete units used for the OFF time (full cycles of line frequency). Referring to the yellow, green, and blue shaded areas of Table -02, each color represents a pair of operating conditions for the same load and firing delay angle. Other than for the large firing delay angle case (yellow), which is not a likely IE operating point for a conventional system, the change in the kVdc level changes significantly for a unit change (1 full line cycle) in the IE OFF time. To achieve optimum IE performance, it is important to be able to finely tune the kVdc level to operate near the back corona point (a small change in Kvdc level is a big deal when the VI curve is nearly vertical or even bending backwards some).

The switchmode unit has the previously mentioned advantages of high frequency switching and controlled turn-on and turn-off of the IGBTs. As a result, both the kV peak and the kVdc levels can be precisely controlled. Conceptually, the thyristor-TR system controls large amounts of energy quite slowly while the switchmode unit controls small amounts of energy both quickly. This situation is analogous to comparing a 10 MHz DSP with a 10 bit ADC to a 1GHz DSP with a 24 bit ADC. Faster switching with finer resolution provides better performance.

Overview of IE Operation on a Sinter Plant ESP:

Two sinter lines at a steel mill each used sixteen units of the 105 kW, 83 kVdc PowerPlus switchmode power supply. The plant operator has indicated that the dust resistivity is in the 10e+12 to 10e+13 ohm-cm range. No internal changes were made to the ESP or the sinter process.

Operating the PowerPlus units in IE mode combined with an optimal rapping strategy, the user opacity decreased to 28% of its value prior to using the PowerPlus units. Furthermore, additional air cleaning equipment downstream from the ESP benefited from less maintenance effort and less number of outages.

During a visit to the site in February 2011, operation of two typical units was examined. The following V-I curve (Figure 2) depicts the DC operation for unit 2-2. Note the steep slope of the curve above 50 kVdc.

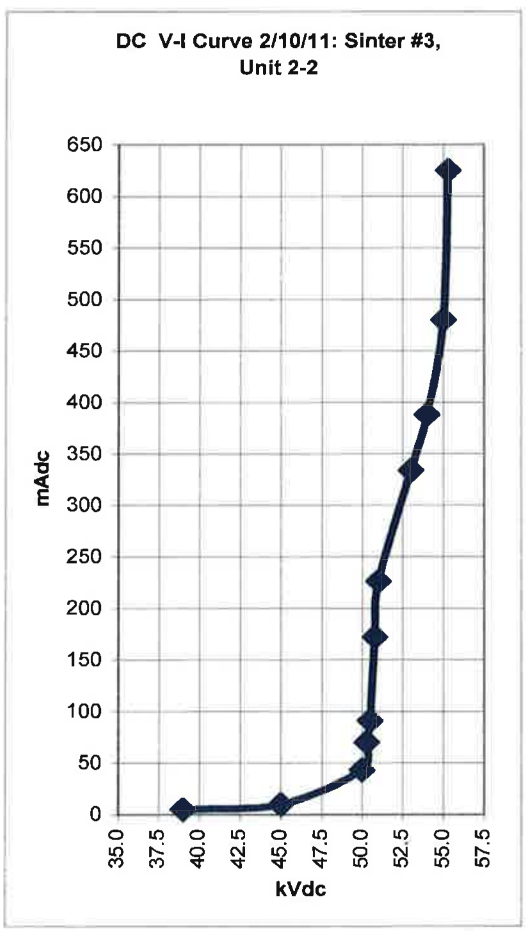

Fig. 04: DC V-I Curve

For this field, the user had settled on an IE ON time of 4.5 milliseconds followed by an OFF time of 37.1 milliseconds. The KV peak voltage was 78 kV; the kVdc average was 36 kVdc, with an average mAdc level of 150 mAdc

The knee of the curve seems to form in the vicinity of 50.5 kVdc and 60 mAdc. The user has elected to operate somewhat higher up the V-I curve around 150 mAdc. Their main reason for selecting this operating point is that the collection performance is exceeding their requirements and the ESP rarely arcs under these operating conditions (78 kV peak, 36 kVdc, 150 mAdc).

Variations in the ON and OFF IE times were made to examine operation of the PowerPlus unit below and above this operating point.

As a figure of merit for ESP performance, NWL uses kV product [6] which is defined as

kV product = kV peak x kVdc (average) (2)

The graph in figure 05 is based on limited data obtained over two days of testing. While this is only a small sample of data, it is still observed that the kV product trends lower as the operating point moves further into back corona. Whether one looks at all the "high" readings, all the "low" readings, or the trend line for the data, the pattern is always a downward movement of the kV product as mAdc level increases further above the knee of the V-I curve.

It should be noted that precise control of the OFF time by the switchmode power supply allows the kVdc operating point to be tightly tuned for optimum ESP collection performance. Using this precise control of ON and OFF times, it becomes possible to operate close to the knee of the V-I curve.

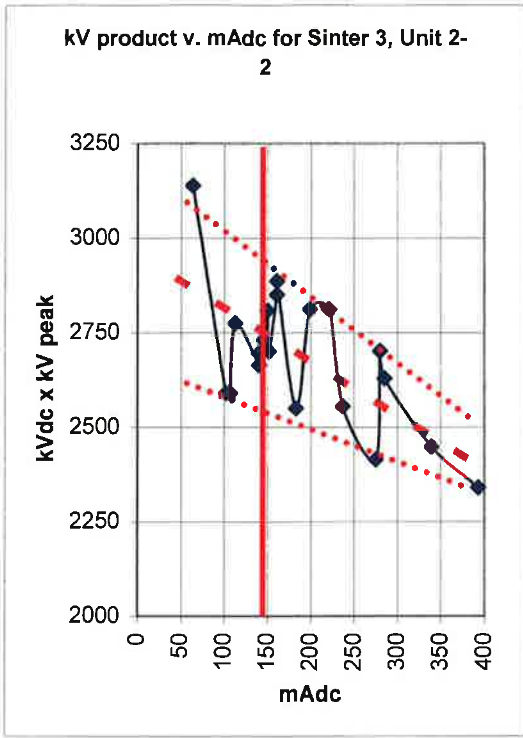

Fig. 05: kV product versus mAdc load. (the vertical red line is the typical mAdc operating point)

Figures 06 display the oscilloscope waveform of the kVdc obtained at settings of 5.0 milliseconds ON and 35 milliseconds OFF. The electrical readings were

78 kV peak, 37 kVdc, 161 mAdc

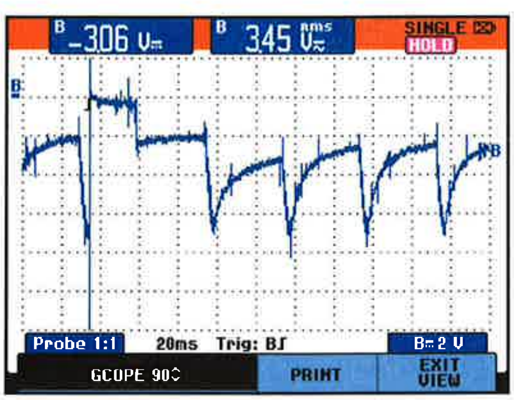

Fig. 06: KVdc for Sinter #3, Field 2-2 vertical scale is 21 kVdc per division

Summarizing this application, the user has installed PowerPlus switchmode power supplies on two sinter lines where previously the only viable solution was the use of pulser units (approximately 60 to 120 usec pulses). With proper IE operation and an optimized rapping strategy, the user has demonstrated successful dust collection for approximately 2 years at a lower investment cost and a lower maintenance cost.

Improving IE Switchmode Performance:

Nichols' and Oglesby's patent [7] on a method of pulse energization is based on the premise that rise time of the kV to the ESP field, especially in the vicinity of the onset of corona, is the critical factor and not pulse width. In moving towards faster kV rise time in IE mode, there are a number of improvements that can be considered when using switchmode power supplies in IE mode. A faster rise time means that a higher current density can be achieved in the ESP field for short periods of time without exceeding the average level at which back corona occurs. The higher this peak short ON time current density can be made (without arcing), the better the ESP can operate with high resistivity dust.

As covered earlier in this paper, many switchmode power supplies, such as PowerPlus, use a topology and control method so as to act like a current source. The basic formula for charging a capacitor is

$I = C \times dv/dt$, re-arranging (3)

$dv/dt = I/C$ (4)

where

I is the output current

C is the ESP filed capacitance

dv/dt is the rate of rise of the output voltage.

Based on this fundamental equation, improvements in IE operation can be made by 1) supplying more current during the ON time and/or 2) charging a smaller capacitor.

There are three means by which more current can be provided by the switchmode power supplies:

1. Power supplies with higher mAdc rating than would normally be used on a field can be installed. Development of power supplies rated up through 200 kW is now underway.

2. Switchmode power supplies that act as current sources can be easily connected in parallel to deliver higher currents. To date, as many as three units have been operated in parallel on an ESP field.

3. Internal changes can be made to the power supply to allow increased output current for ON times up to a specified level. Care must be exercised in evaluating the thermal and power cycling of components when this alternative is used.

In conjunction with the power supply enhancements just described, the ESP manufacturer, for major rebuilds and new ESPs where high resistivity is an issue, might choose to utilize greater segmentation of the ESP fields. Not only does increasing the number of fields lead to lower capacitance and faster charging, historically, it has also been established that segmentation, in itself, leads to greater collection efficiency.

Additional fields, larger power supplies, or an increased number of power supplies mean increased costs. It may be that this extra cost is preferable to having to use pulse power supplies.

Conclusion:

In conclusion, we have shown that the high speed switching of a switchmode power supply enables precise control of small increments of IE ON and OFF times. When compared to the conventional thyristor- TR system, this fine resolution of the ON and OFF times allows for more exact tuning of the operating point for high resistivity dust loads.

An example of successfully using switchmode IE power supplies on a sinter line in lieu of pulse power supplies has been presented. The implication is that switchmode units combined with optimal rapping strategies are an alternative where previously pulse power supplies were the only choice of solutions.

Finally, options were presented on how to apply switchmode power supplies to obtain a faster rising voltage during the IE ON time.

Literature

[1] White H. J., "Industrial Electrostaic Precipitation", Addison_Wesley, 1963, pg 319-329

[2] Reyes V. and Lund C., Full Scale Test with Switchmode Power Supplies on an ESP at High Resistivity Operating Conditions, Proceedings ICESP VIII, Birmingham AL, 2001

[3] Klippel N., Schmidle H., et. al., The Evolution of Back Corona conditions in an ESP, Proceedings ICESP VI, Budapest, 1996

[4] Nichols, G., Report: A Study for Dust Removal by Polarity Reversal (for NWL and EPRI), 2001

[5] Rombaut C., Seguier G, et. al., Power Electronic Converters, Volume 2, McGraw- Hill, 1987, pg 7

[6] Altman R., Guenther R., US Patent 7081152, 2006

[7] Nichols G., Oglesby, S., US Patent 5972076, 1999