# Design Aspects of Large-Area Coating Supplies

*Eric Seymour, Annabelle Pratt, Ph.D., Advanced Energy Industries, Inc.*

*Successful glass coating requires that many systems and processes be optimized. Arguably one of the most important is the control of the plasma process itself, which relies on the ability of the process power supply to maintain stable plasma and control process parameters such as power, voltage, or current.*

*Ideally, a process power supply should be able to run stably over a wide range of processes without reconfiguration. For this, it is essential that the supply be well suited for this specific, highly non-linear load.*

*This paper will discuss aspects of AC power supply designs often seen in high power, large-area coating with an emphasis placed on the LCC resonant topology. Influence of the plasma load on resonant topology behavior will be considered.*

*Additionally, other performance aspects of large-area coating supplies will be presented. While process control is paramount, the interaction of the process power supply with the power system has a significant impact on overall plant operation. The effect of input power factor and harmonic injection will be considered. Supply designs with high power factor and minimal harmonic injection offer substantial benefits with regard to plant infrastructure, utility surcharges, and emerging regulatory constraints.*

*From the above discussion, it can be seen that it is important to choose an appropriate power supply design both for process control of the plasma and interconnection with the power system.*

contents



## Introduction

Large-area glass coating in recent years has seen a significant adoption of dual magnetron sputtering (DMS) processes. This has resulted in the worldwide installation of a large number of high power AC supplies. Such supplies are presently available in a surprising breadth of designs with widely varying operational characteristics. A consequence of this, coupled with the considerably complex behavior observed in AC plasmas, is a degree of performance variation across available power supply offerings not seen in the preceding generations of DC supplies. An effort will be made here to understand why this is the case by analyzing the relationship between an AC plasma and the supply running it.

In addition to high power AC process-side performance characteristics, this paper will consider facility-side constraints as evaluation criteria for present and future high power plasma process supplies.

# Plasma Performance

## General Supply/Plasma Characteristics

The two major design categories for AC switch-mode supplies used in large-area glass coating can be defined as resonant and non-resonant with each having several distinct sub-categories. Some distinguishing characteristics between the two are that resonant supplies produce a sine wave output accompanied by a variable gain characteristic as a function of load impedance while non-resonant designs produce square wave outputs without variable gain. Although it is not the objective of this paper, it is worth noting that considerable industry effort has been expended to determine which genre of power supply is best suited for AC plasma service. To the authors' knowledge, this has resulted in no definitive conclusion.

However, it is apparent that resonant AC designs have achieved market prominence. The reasons for such a preference are likely not due to any inherent plasma performance benefit over non-resonant designs but rather cost, complexity, and robustness. The reason for this has to do with the particular demands placed on an AC supply by the plasma load.

In order to minimize delivered energy into process arcs, power supplies are often designed as current sources. However, when an AC plasma is operated with a non-resonant current source, the result is often a very high and destructive voltage spike every half cycle. Such a design either must be overbuilt for voltage tolerance with the hope that voltage spikes never surpass the damage threshold, or it must absorb the spike by reprocessing energy every half-cycle using additional hardware. These constraints have a negative effect on the robustness and cost of non-resonant supplies.

Generally, resonant supplies have avoided this problem by appearing to the plasma as something between a current source and a voltage source. They can accommodate the demanding reactive power needs of AC process plasmas without added complexity, cost, or loss of reliability.

However, the physical simplicity of resonant designs is offset by their complicated dynamic interaction with the plasma. The following presents some dynamic performance characteristics of the LCC resonant topology.

## LCC Design

Figure 1 shows the LCC topology used for high power AC plasma and its corresponding calculated resonant voltage gain curves for resistive loads. The design is frequency modulated in the indicated range with the highest operating frequencies correlating to the lowest power levels. The gain curves show the ratio of output to input sine wave magnitudes (in reality, the input is a square wave and the output is nearly sinusoidal).

As the topology is modulated up in power delivery, the gain curves spread further apart from one another. This is similar to stating that, as power is increased, the topology transitions from voltage source behavior to current source behavior. However, aspects of both are maintained throughout all areas of operation, thus avoiding the aforementioned current source transient problem that affects non-resonant supplies.

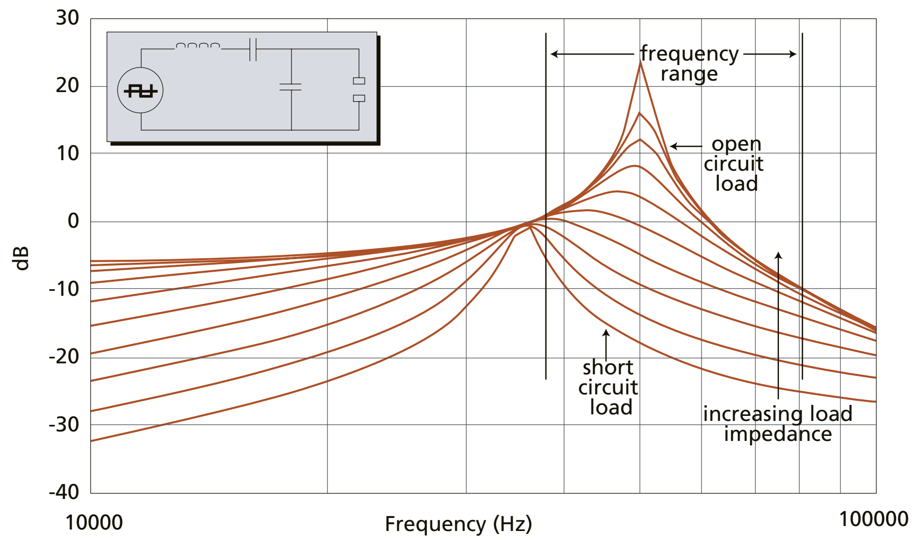



Figure 1 LCC topology with gain curves

Figure 3a shows the calculated V/I plots for three theoretical loads, and Figure 3b shows the calculated RMS voltage gain curves for the LCC resonant topology with a square wave input voltage for the three respective loads [1]. All three loads have the same output RMS voltage at 53 kHz which results in 75 kW of delivered power. Load 1 is a linear, resistive load and loads 2 and 3 are non-linear loads, respectively exhibiting constant current and constant voltage behavior, modeling the behavior of the measured load in Figure 2.

Experimental evaluation proved the LCC topology to be easier to stabilize on plasma loads than other resonant topologies evaluated. The experimental results also indicated that the stability characteristics gave the design the best chance of avoiding customized topology or control alterations as it entered service. Operational data has confirmed this estimation, as the LCC topology has, in five years of service, required no process-based topology or control adjustments in the high power glass-coating market. As the next section describes, this is especially challenging for AC plasma applications.

## AC Plasma Characteristics

DC plasma loads are often characterized as a near-constant discharge voltage on a V/I plot. While the constant-voltage DC plasma characteristic certainly constitutes a non-linear load, it is of a generally expected shape. Similar plots of AC plasma RMS V/I curves under constant process conditions show a similar shape. However, the breadth of encountered process loads is more fully understood by inspecting real-time V/I plots of AC plasmas. As Figure 2 shows, the instantaneous V/I characteristic can range from the expected constant-voltage load in Figure 2a to a constant-current load in Figure 2b. The curves change shape as a function of sputtered material, gas composition, and the sourcing power supply.

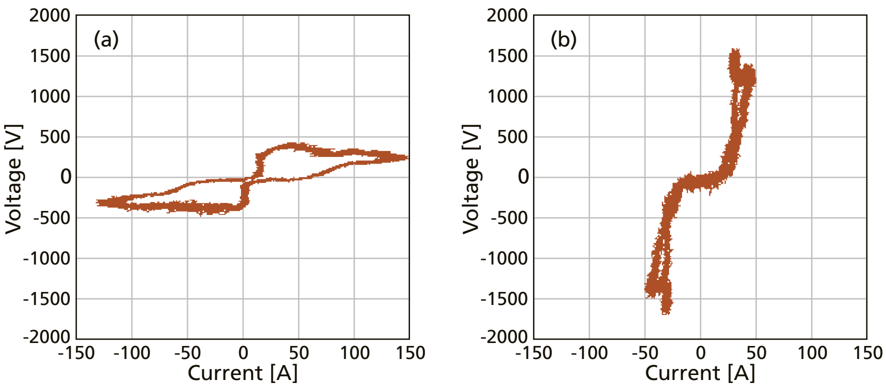



Figure 2 Measured V/I plots for a) reactive and b) metallic Al DMS process

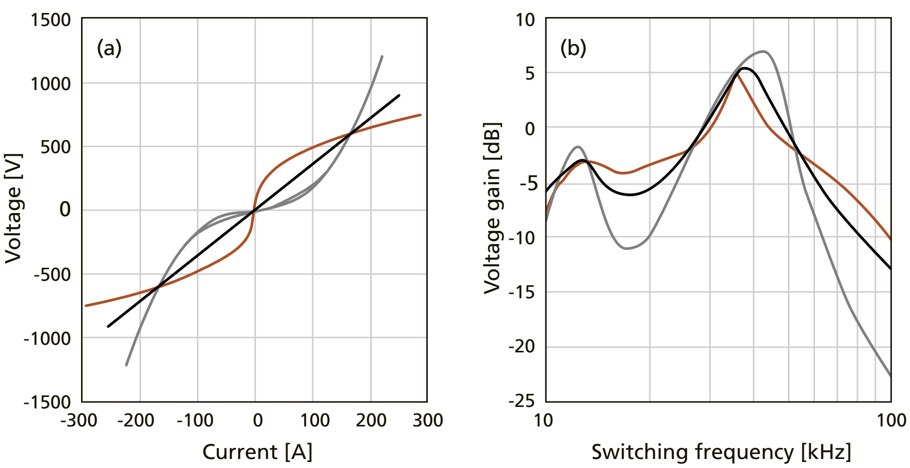



Figure 3 a) Load characteristics and b) gain curves for each respective load

Unlike the idealized gain curves of Figure 1, which are associated with different linear loads, the gain plots in Figure 3b depict gain curve distortion caused by non-linear loads. Such gain distortion can result in a wide variety of behavior, making controller design difficult.

## Supply-Facility Performance

### Operational Cost Analysis

Improvements in power supply process-side performance have resulted in dramatic operational cost and efficiency benefits. Achieved process stability at ever-higher power levels has afforded increased line-speed and improved use of capital equipment. Better arc handling has improved target-use, even making damaged target reclamation possible. Insensitivity of power supply configuration to process conditions has decreased product changeover times. Process-side performance indices like these have reached high levels of visibility for two reasons: first, the cost consequences are large and second, there is the correct belief that such areas are controllable and capable of continuous improvement.

There is another performance aspect with considerable financial consequence that receives far less attention: electricity costs. Coater process power supplies are the largest electrical consumers in coating facilities. As such, they largely define the plants' power factor and power quality. Power factor is often reflected in the utility bill as a reactive power charges or an adjustment to demand kW charges, while power quality issues such as current harmonics and voltage distortion are receiving increased scrutiny by utilities and regulatory bodies [2].

If one assumes that a modern large-area glass coater operates 24 hours per day, 28 days per month with energy rates between 0.03 and 0.045 USD/kWh, then energy charges fall in the range of 40,000 to 60,000 USD/month. Industrial customers face additional billing that is a function of kW loading. These are meant to offset utilities' fixed operating costs and are known as *demand charges*. They can easily add tens of thousands of dollars to the energy charges. However, when power factor and *peak* demand surcharges are added, the monthly bill can double. Unfortunately, while energy charges are easily understood, there is a large degree of variation in the billing formulas for reactive power and demand charges [3].

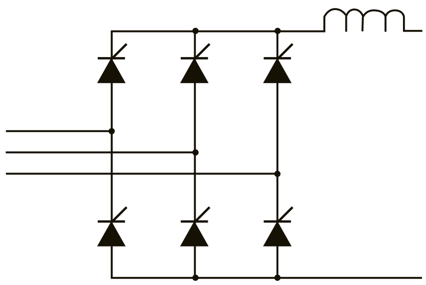
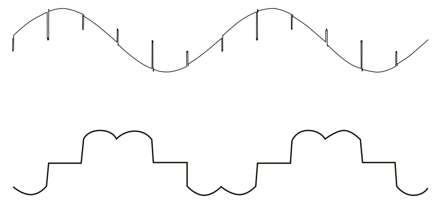
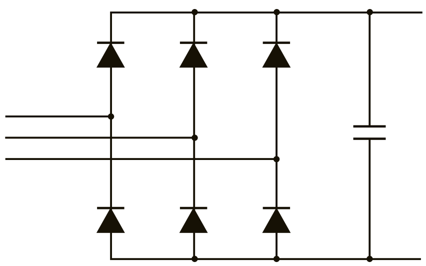
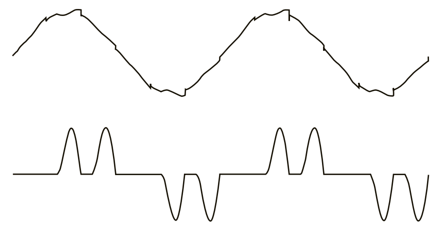
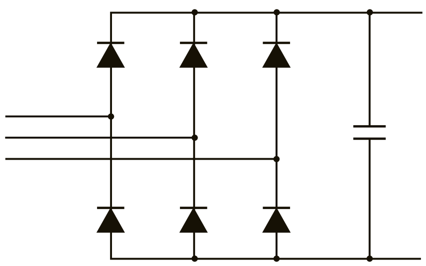
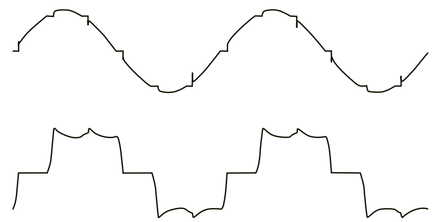
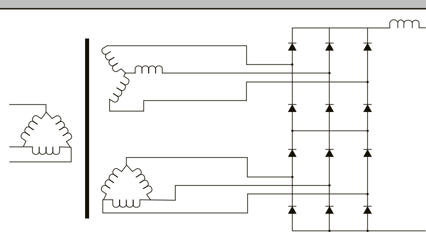
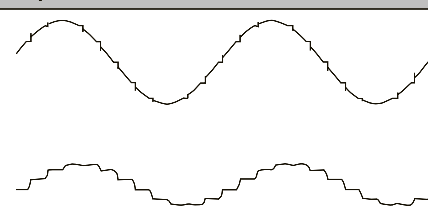
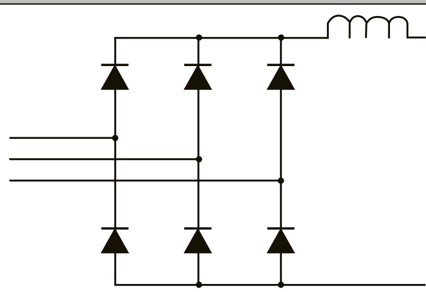
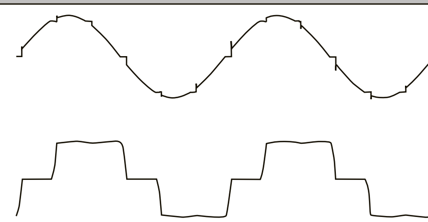
Since coating operations often work in concert with tempering or float operations, actual facility energy and demand charges can be hundreds of thousands of dollars per month. Since power factor and peak demand charges, when applied, are often non-linear, a modest improvement in facility power factor and peak kW demand (often including a power factor billing adjustment) could conceivably cut more from the utility bill than the energy consumption costs for the coater itself. Some facilities are so affected by this problem that consideration for the first time has been given to diesel and turbine generators used to cut peak demand. It is therefore vital that facility power factor be held above a utility's trigger level, usually between 0.85 and 0.9, below which surcharges are applied [3]. This leads to an exploration of process power supply front-end design and its effect on facility power factor and power quality.

## Supply Rectifier Design

Power supplies used in large-area glass coating require the initial conversion of 3 phase AC to DC (most supply designs then process power further in subsequent stages). How such rectification is implemented determines eventual input power factor and harmonic loading. Front-end design also affects supply control stability and immunity from aberrant electrical system conditions. Table 1 shows several rectifier designs presently employed in large-area coating operations. The line-to-line voltages and phase currents are representative of 100 kW loads with 100 μH of source inductance. The input power factor (p.f.) and total harmonic distortion (THD), which is the ratio of harmonic content to fundamental content of the input current, is listed for each design.

The phase controlled SCR bridge in Table 1a is a common design for high power DC supplies. Provided that the input scaling from the feeding isolation transformer (not shown) is such that the supply is capable of voltages as high 1000 VDC, common process voltages in the vicinity of 400 VDC require an excessively large displacement (firing) angle. At high power levels this results in excessively poor reactive power consumption due to both fundamental phase lag and harmonic content. Traditional methods to address this, such as power factor correction capacitors, may cause adverse resonances excited by the harmonic current injection. Additional tuned harmonic filters or active filters may be required to ultimately correct the poor power factor.

Table 1 Input line-to-line voltage and phase current for various high power rectifiers at 100 kW plasma load power [4]

| Design | Line-to-Line Voltage Phase Current |
|---|---|
| **a) 6-Pulse SCR Phase-Controlled Rectifier Driving Large Inductor** | **p.f. = 0.40, Current THD = 30%** |
|  |  |
| **b) 6-Pulse Diode Rectifier Driving Large Capacitor** | **p.f. = 0.70, Current THD = 101%** |
|  |  |
| **c) 6-Pulse Diode Rectifier Driving Small Capacitor** | **p.f. = 0.94, Current THD = 30%** |
|  |  |
| **d) 12-Pulse Diode Rectifier** | **p.f. = 0.99, Current THD = 13%** |
|  |  |
| **e) 6-Pulse Diode Rectifier Driving Large Inductor** | **p.f. = 0.96, Current THD = 24%** |
|  |  |

The designs in Table 1b through 1e are diode rectifiers used by modern switch-mode supplies. In such designs, the power modulation to the plasma load is accomplished by subsequent power processing stages (not shown). Unlike the SCR rectifier in 1a, they do not cause a fundamental displacement angle.

Table 1b shows a design with a six-pulse diode rectifier feeding a large capacitor (> 1000 μF). The design is low cost, offers good control stability, and is largely immune to input transients. However, the capacitor is responsible for the poor input power factor. Worse still, since the fundamental components are in-phase, the poor power factor is due entirely to harmonic content. Furthermore, the harmonics and power factor become worse as the input source impedance is reduced.

The design in 1c is similar to 1b with a greatly reduced DC capacitance (< 10 μF). This design is very low cost and is common in power supplies of ≤ 20 kW. The odd shape of the current pulses is caused by the negative impedance behavior exhibited by power supplies. That is, an increased input voltage results in *decreased* current. For related reasons, this design is susceptible to aberrant input conditions and suffers from potential control instability should the source impedance become too large. Providing adequately low source impedance for such designs becomes a problem at high power levels.

A better, albeit more expensive, solution is shown in Table 1d. Rectifiers with 12 pulses and higher (not shown) require specialized isolating magnetics. Since AC plasma process supplies almost always contain high-frequency isolation transformers, such isolation redundancy is often viewed as excessively expensive. Also, there often is not sufficient available footprint in coating facilities for full-kVA line-frequency transformers. Multi-pulse rectifiers (12 pulses and higher) are typically used for large rectified loads of many MW.

The design shown in Table 1e provides good power quality and power factor and is immune to input transients. While it is more expensive that the design in 1c, its stability characteristics are not contingent on facility specific parameters such as input impedance. This input stage is preferred because it provides a good utility interface for high power AC supplies in a smaller footprint than multi-pulse rectifiers.

## Conclusion

Due to the introduction of DMS, AC power supplies have proliferated in high power glass coaters with resonant designs being the most prevalent. The non-linear nature of AC plasma loads alters resonant topology behavior and makes controller design difficult, as discussed in some detail for the LCC resonant design. This highly variable and load-dependent behavior is made even more confusing for consumers of high power AC plasma processing supplies because such characteristics vary widely from design to design. The success seen by the LCC topology in running stable plasma over a wide variety of processes is due to an effort meant to implement a resonant design whose control is minimally affected by non-linear loads. An investment made in providing AC supplies with a high performance utility interface may offer financial benefit for glass coaters far in excess of their cost.

## Acknowledgements

The authors are grateful to Don van Zyl of Advanced Energy for his assistance with nonlinear circuit modeling; Brian Basso, Dennis Brabender, Michael Potter, Jeff Tramel and Mike Wade, all of Cardinal Glass Industries; and Pat Ellwood of SME Inc. of Seattle.

## References

[1] R.J. Gilmore, M.B. Steer, Int. J. Microwave and Millimeter-Wave Comput.-Aided Eng., 1, no. 1 (1991), 22.

[2] E. Reid, IEEE Trans Ind Appl, 32, no. 3, (1996), 625.

[3] F.L. Alvarado, R. Broehm, L.D. Kirsch, A. Panvini, in: Proceedings: 1996 EPRI Conference on Innovative Approaches to Electricity Pricing, EPRI, Palo Alto, U.S.A., March 27-29, 1996, p.24-1. TR-106232. [http://peru.ece.wisc.edu/alvarado/1996/lajolla96.pdf]

[4] Simulation performed with NL4 Ver. 2.01, Copyright 2000-2003 by A. Smirnov.

ADVANCED ENERGY®

Advanced Energy Industries, Inc. • 1625 Sharp Point Drive • Fort Collins, Colorado 80525
T: 800.446.9167 or 970.221.4670 • F: 970.221.5583 • support@aei.com • www.advanced-energy.com

© Advanced Energy Industries, Inc. 2004
All rights reserved. Printed in U.S.A.
SL-LAreaCoating-270-01 0M 11/04

| United Kingdom | Germany | Korea | Japan | Taiwan | China |
| --- | --- | --- | --- | --- | --- |
| T: 44.1869.320022 | T: 49.711.779270 | T: 82.31.622.0555 | T: 81.3.32351511 | T: 886.2.82215599 | T: 86.21.5857.9011 |
| F: 44.1869.325004 | F: 49.711.7778700 | F: 82.31.622. 0556 | F: 81.3.32353580 | F: 886.2.82215050 | F: 86.21.5857.9003 |



Advanced Energy® and AE® are trademarks of Advanced Energy Industries, Inc. • Applied Materials®, Electra CU®, and SlimCell® are trademarks of Applied Materials, Inc.
IBM® is a trademark of International Business Machines Corporation. • Novellus® and SABRE® are trademarks of Novellus Systems, Inc.
Semitool® and Paragon® are trademarks of Semitool, Inc.