Performance Considerations of High-Power AC Plasma Deposition Power Supplies

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The purpose of this document is to compare the behavior of several presently available high-power (>50 kW) AC supplies used in dual-cathode sputtering. Emphasis is placed on performance aspects that affect the plasma process.

Supply Types

There are presently two predominant types of high-power AC supplies used for plasma loads. Both are considered resonant in nature. The first and oldest is the parallel resonant design. Such supplies are available from several sources. Despite some subtle design differences between manufacturers, such power supplies are fundamentally similar and can be treated generally. The second type of AC power supply is the LCC resonant type. The only present example of this is Advanced Energy's Crystal® series.

The following analysis shows relevant aspects of design from the user's perspective. Elements of power supply topology that are not relevant to process performance are shown symbolically (voltage and current source symbols) and are not described in detail in this paper.

Parallel Resonant Supplies

Parallel resonant supplies have this general topology:

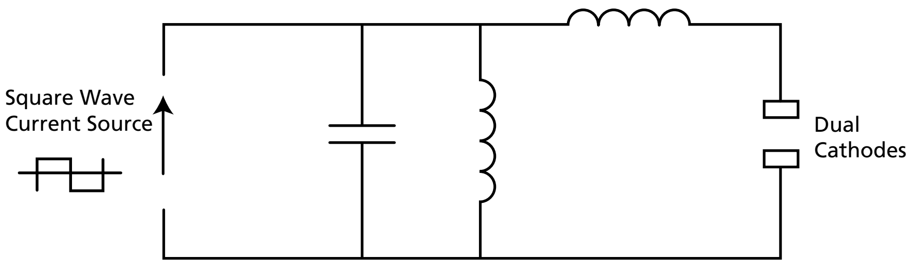

Figure 1. Typical parallel resonant topology

The topology is similar to that used in induction heating applications (in the case of induction heating, a resistive load would be coupled through the shunt induction coil instead of by direct connection). The resonant design causes a variable gain that allows for a broader impedance band (load matching) than would otherwise be possible with a non-resonant design of similar cost. What this means, is that for extremely low impedance loads, the current delivered to the load from the network can be far greater than the current supplied by the square wave current source. This can be seen by the following current gain curves.

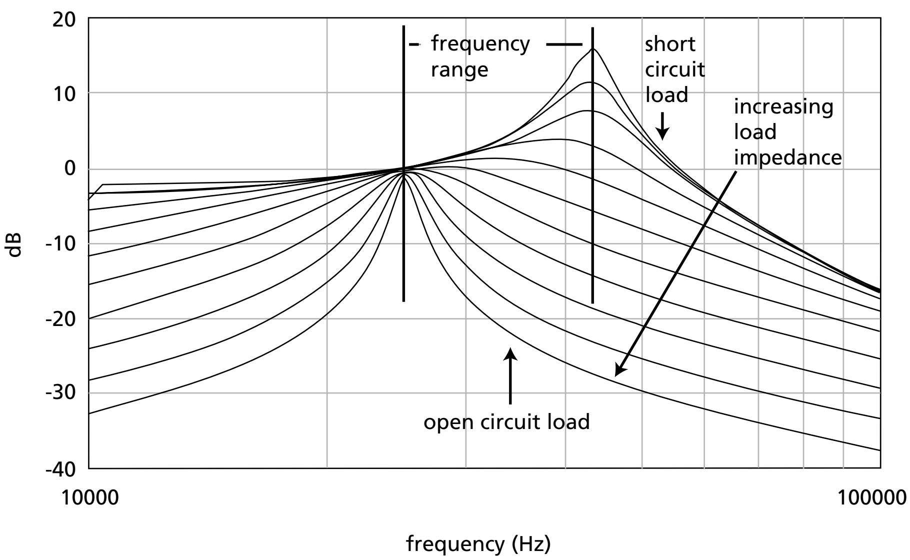

Figure 2. Parallel resonant typology with gain curves

As can be seen from the gain curves, the resonant frequency can vary from around 25 kHz into an open load to a higher-gain, higher-frequency, short-circuit load point. As will be shown later, the behavior suggested by these curves is vital to understanding plasma process stability.

LCC Resonant Supplies

The Crystal LCC resonant supply has the following topology:

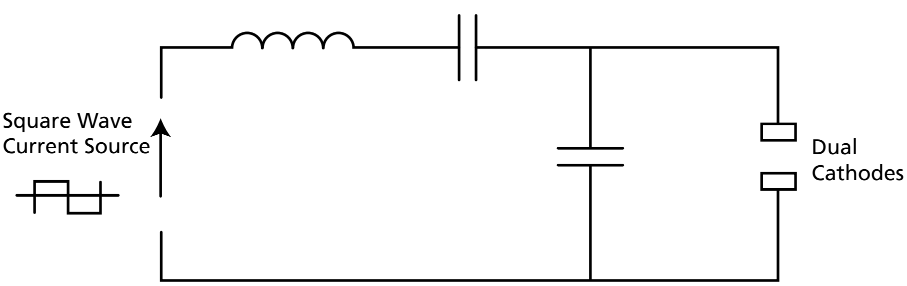

Figure 3. Crystal LCC resonant typology

The Crystal LCC resonant design was specifically built for driving plasma loads. Like other resonant designs, it has a variable gain that allows for large load impedance swings at full power delivery. It behaves, however, unlike other resonant designs for three main reasons. First, it is intrinsically stable, while driving plasma loads. Second, it delivers very little energy to an arc. Finally, it can also produce extremely high ignition voltages.

The gain curves for the Crystal LCC resonant supply show themselves to be the opposite or the dual of those for the parallel resonant design.

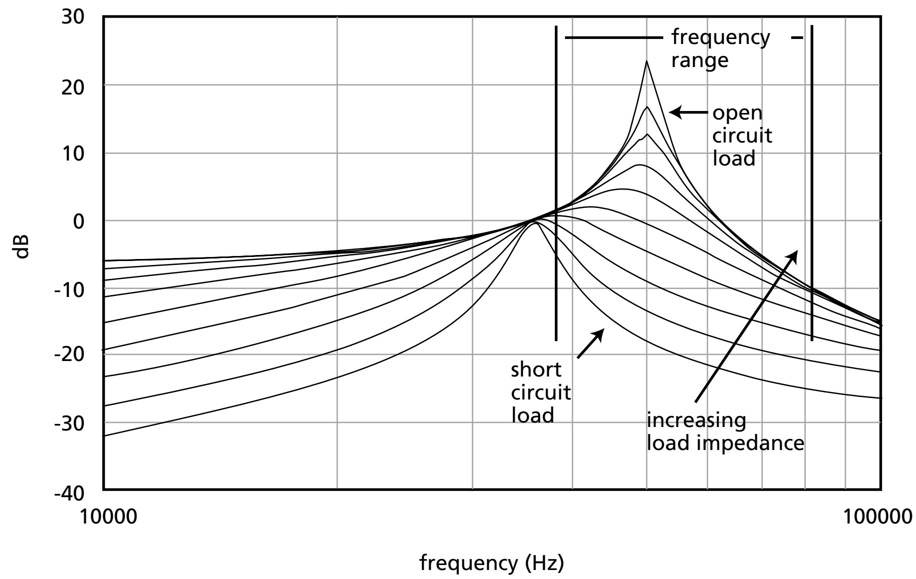

Figure 4. Crystal LCC resonant typology with gain curves

The highest gain curves correspond to the highest plasma impedances. This will be shown to be vital to process stability.

Plasma Stability

Although dynamic supply-plasma stability (i.e., arc handling) is discussed later, it is beneficial to look first at static process stability to address historically observed process stability problems in systems that do not suffer from arcing and have constant inputs (pumping, gas inputs, power set point, etc.). To do this, it is first necessary to look at a hypothetical plasma.

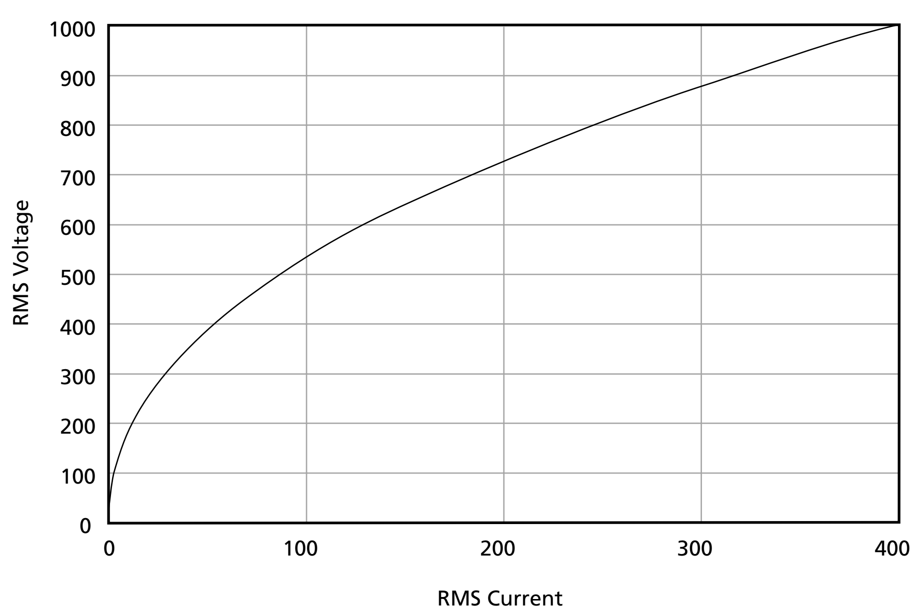

Figure 5. Plasma voltage/current curve

This plasma voltage/current curve has the typical non-linear zener diode behavior (keeping in mind that a real plasma would probably not be viable below 300 V). Of course, curves like this vary with pressure, temperature, gas composition, and many other factors. For now, it is assumed that all variables, other than delivered power to the plasma, are constant. From the points that comprise this curve, complex power can be determined for any point as well as the impedance magnitude. Power then can be plotted as a function of impedance.

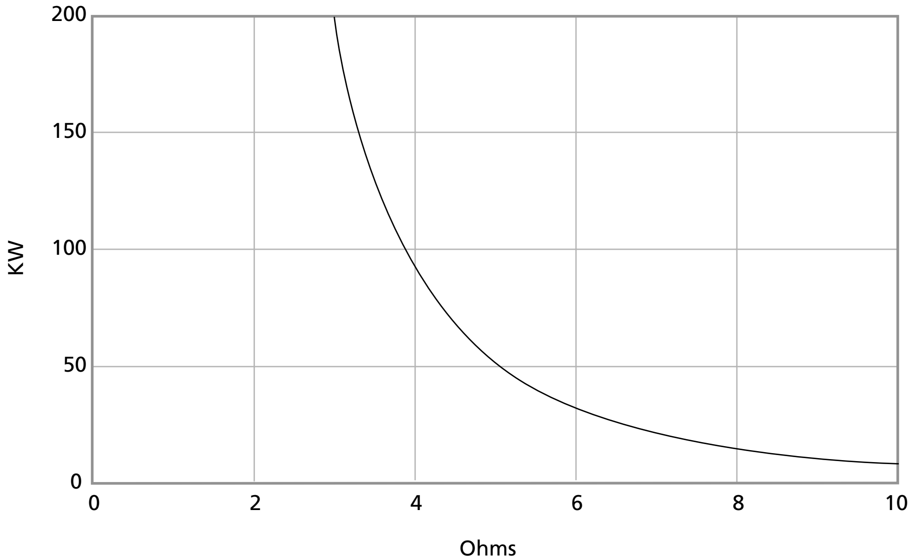

Figure 6. Plasma power/impedance curve

The curve shows that delivered power and impedance in a plasma have a dependence not seen with an ideal resistor (whose resistance is not dependent on anything). In an effort to understand the nature of intrinsic stability in a supply-plasma combination, it is useful to imagine the supply operating at a fixed point without the intervention of control loops.

The next graph shows the same plasma power/impedance curve with the addition of two other plots. The dotted hyperbolic curve shows delivered power as a function of load impedance for a fixed voltage source of 600 V. The linear curve shows the delivered power as a function of load impedance from a current source operating at a fixed level of 150 A.

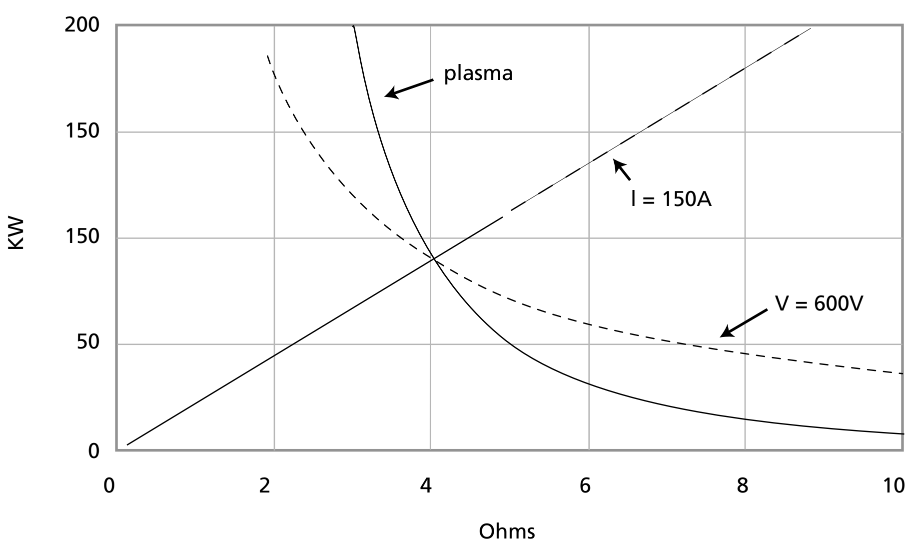

Figure 7. Power delivery as a function of impedance

The actual operating point is where the power supply curve and the load plasma curve cross (identical crossing points for both the voltage source and the current source were selected). Notice how the voltage source curve has a similar shape to the plasma curve. This can be reason for concern in reactive processes where there is a strong dependence between consumed, reactive gas and process pressure. Since the plasma curve can change dramatically, there is the possibility that the voltage source curve could cross in more than one location, or even cause a drifting phenomenon. It is partly for this reason that true voltage sources have fallen out of favor for plasma loads.

Parallel Resonant

The final step in analyzing static stability is to look at the resonant topology. The parallel resonant topology has the following operating point into the same 4 Ω, 90 kW load.

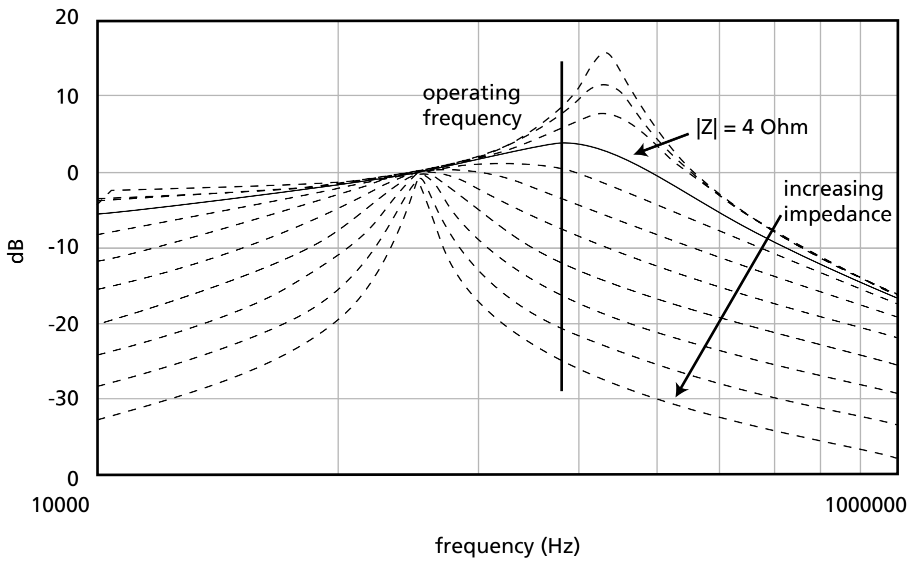

Figure 8. Parallel resonant current-gain curves

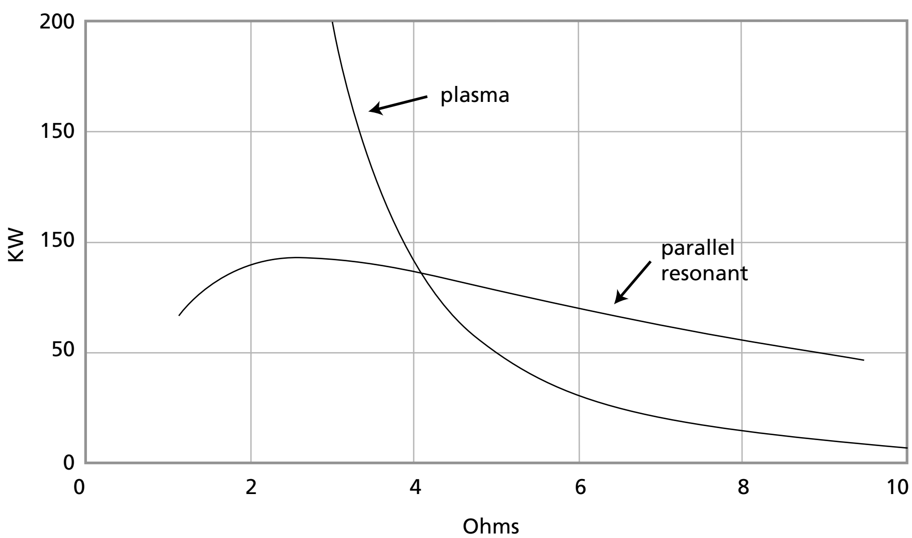

Figure 9. Parallel resonant power delivery as a function of impedance

It can be seen that a parallel resonant source looks very much like a voltage source to plasma loads. This is a curious result for a circuit that is fed with a current source. The conclusion is that the drive to a given resonant circuit is not particularly relevant to the load.

Parallel resonant sources do appear like current sources to the load for fractions of a cycle due to the inductor that is in series with the load. This also does not appear to be important to the circuit's plasma stability characteristic. It is a topology's performance over multiple cycles that determines whether it is stable or not.

On a multi-cycle timeframe, the parallel resonant topology appears like a voltage source because in those cases where the plasma impedance is perturbed to a higher level, resonant gain and power delivery go down. Under certain situations this could cause a positive feedback situation where the plasma keeps increasing impedance, while the resonant gain and power descend until the plasma goes out or begins to oscillate with reactive gas pressure changes.

AE Crystal LCC

This leads to the next question: are the resonant converters voltage sources or current sources? Starting with the Crystal LCC, a gain curve and operating frequency can be selected in the following figure that correlate to the 4 Ω, 90 kW operating point shown in Figure 9.

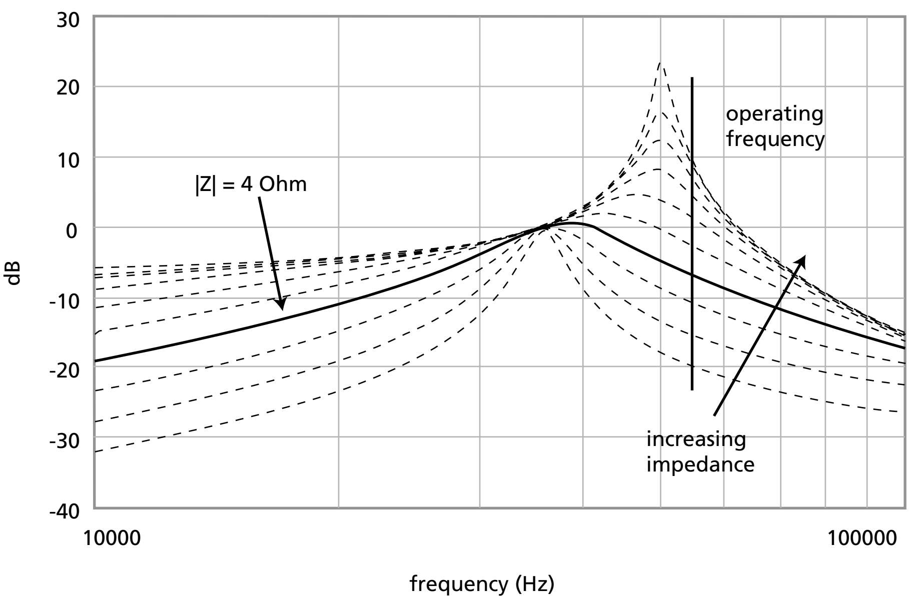

Figure 10. Crystal LCC resonant voltage-gain curves

Now at this fixed operating frequency, what happens if the plasma impedance is perturbed either higher or lower? Any attempt by the plasma to increase its own impedance will cause the Crystal LCC to shift to a higher gain curve (one of the higher dotted lines). Any fall in impedance causes the Crystal LCC to shift to a lower gain curve. The result is the following power delivery as a function of impedance curve (printed with the plasma curve seen previously).

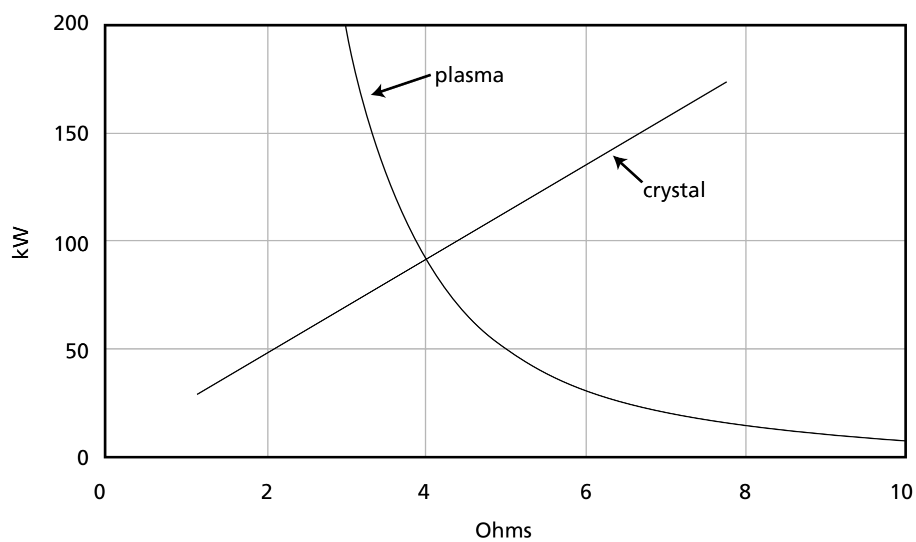

Figure 11. Crystal LCC power delivery as a function of impedance

This result shows that the Crystal LCC responds to plasma perturbations in the same manner as a true current source. Increased plasma impedance results in higher gain. Higher gain causes greater power delivery. Greater power delivery forces the impedance back to the stable operating point.

Controls, Tuning, Filters, and Measurement

Of course, parallel resonant topologies do not exhibit continual instability. Their history suggests, that despite the occasional process problem (often silicon processes), they can be made to work, given enough effort. That effort comes in the form controls, tuning, and filters.

The control loops implemented
in the Crystal LCC have a relatively easy task. Their job is to maintain a prescribed point within an intrinsically stable system. The conceptual analogy often used to describe this is drawn in the following figure.

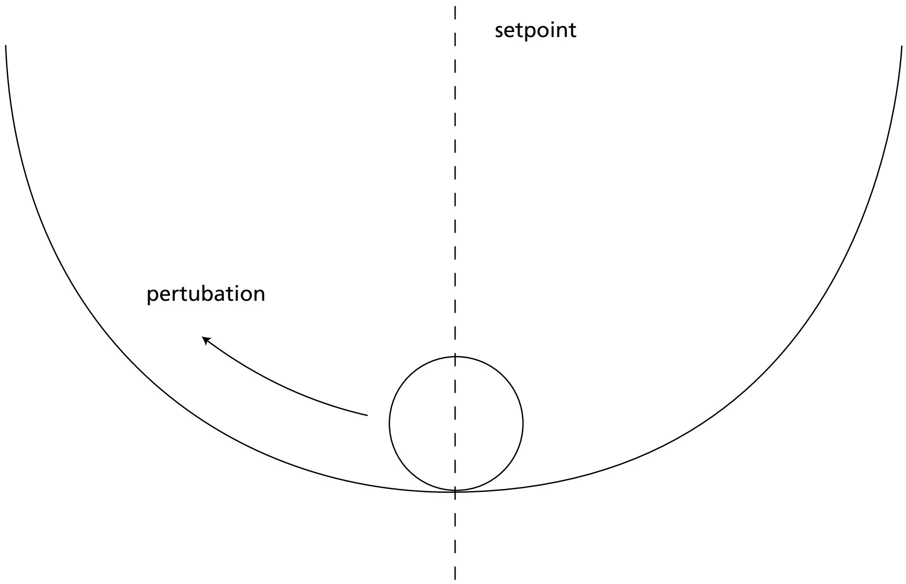

Figure 12. Conceptually stable system

Conceptually, the control loop must keep the ball over the dotted line. When the ball is inside the trough, this is a trivial task.

The control loop of a parallel resonant supply has a much greater challenge. Its conceptual task can be drawn as follows.

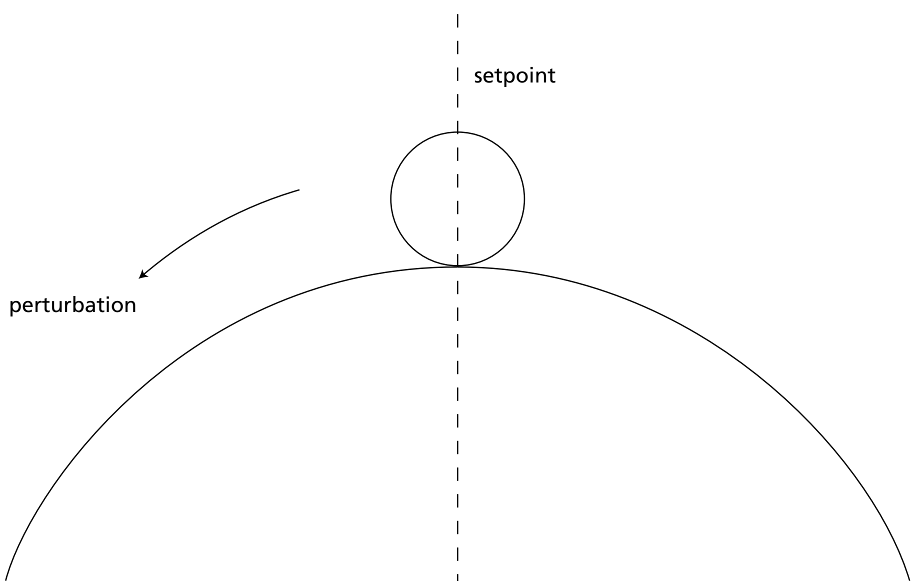

Figure 13. Conceptually unstable system

This situation is further complicated by the fact that, unlike the Crystal LCC, parallel resonant supplies must control two dimensions at once: current injection to the network and drive frequency. (The Crystal LCC controls only frequency.)

Since stability is not intrinsic to the parallel resonant design, the control loop must attempt to stabilize the system. When such a situation occurs, it is beneficial to completely understand the nuances of the system being stabilized. The problem comes from the fact that no one has ever created a thoroughly satisfactory model of a plasma in this regard. At the very least, it is extremely non-linear. Unstable non-linear systems have historically proven to be very difficult if not impossible to stabilize using traditional linear control methods.

As a result, the effort to stabilize parallel resonant systems has focused on hardware solutions. These solutions have followed an accumulated knowledge approach. Despite many years of running processes with such systems and finding ways to make them work one at a time, new instabilities are still being discovered. Existing hardware solutions not only consist of the persistent tuning of the resonant network (in an effort to hopefully find a stable operating point), but also involve the custom installation of circuits known as cathode filters.

What little is publicly known about cathode filters can be seen in U.S Patent # 5,807,470 by Szczyrbowski and Teschner. The patent discloses a power/impedance curve that shows the supply-filter combination acting as a near perfect voltage source as shown earlier in this paper. The stated purpose of the filter is to improve its arc recovery characteristics. This is discussed further in the next section under arc handling.

Arc Handling

One of the biggest challenges faced in reactive sputtering is coping with the interdependence of the chemical consumption of reactive gas, operating pressure, and plasma operating voltage. Any change in the gas consumption rate can have a negative effect on process stability. One obvious example of such an event is the handling of an arc.

The consequences of handling arcs (by temporarily turning off the plasma) are especially important in modern, high-deposition, rate-reactive (transition mode) processes. It has been determined that interruptions in plasma operation as short as 15 msec can cause a relevant reactive gas pressure burst. Once a pressure burst has occurred, it is very likely that recovery measures must be taken in order to return to the desired process operating point. It is therefore necessary to look at the arc handling characteristics of the two supplies described in this paper.

Parallel Resonant

The parallel resonant design also handles arcs by shutting down the drive circuitry and waiting a prescribed time before re-ignition. Arc detection methods vary between manufacturers, but for the purposes of this paper it is assumed that the detection methods are sufficiently fast and reliable. The problem arises with the large amount of stored energy in the parallel resonant circuit and the large percentage of that energy that is delivered to the arc after detection and drive shutdown. The voltage and current ring-down is on the order of several hundred µsec. Delivered arc energies are at least an order of magnitude higher than with the Crystal LCC and probably much greater. The required off-time is on the order of 30 to 100 msec. Shorter durations are certainly possible from the drive perspective and have been attempted, although with disappointing results. Shorter off-times have presumably failed to allow sufficient cooling time for the damaged target.

The long arc-handling duration required with parallel resonant supplies causes the reactive gas pressure burst mentioned earlier. The historical remedy for this has been to apply additional power after recovery from an arc. The purpose of this is to consume the additional gas before the targets become poisoned and process stability is lost permanently. One of the methods by which additional power is delivered from parallel resonant supplies is to take advantage of their voltage source behavior, since as process impedance falls, parallel resonant supplies deliver more power. This behavior is enhanced by the installation of the cathode filters described in the previous section. Although a detriment to overall plasma stability, this approach to excess gas consumption was obviously developed out of necessity. Since the debut of supplies with much faster arc handling, this technique of applying additional power after an arc is no longer required.

Another approach to limiting the negative consequences of parallel resonant arc handling performance is to simply ignore arcs that are not severe. Sometimes arcs in AC systems will clear themselves at the end of a half cycle. Unfortunately, the only way to determine whether an arc is severe and requires active measures is to wait until it has already caused so much damage that it can no longer be ignored. For this reason, the Crystal LCC handles every arc without waiting for it to become severe.

Another result of a long arc-handling time is that it is often visible on the conveyor process substrate (usually glass) as banding. This problem applies to all processes: metallic, poisoned, and transition. The remedy for this has been to parallel many cathode pairs for a given layer with the hope that a band from any one supply would not be visible.

The last problem with a long arc clear time is that it precludes the use of anything other than well-behaved targets. Targets can develop physical imperfections (often manufacturing defects uncovered as they erode) that precipitate heavy arcing, often in the middle of a process run. With clear times on the order of many tens of msec, parallel resonant supplies can tolerate only a few arcs a second before they fail to deliver any relevant power at all. With the Crystal LCC, such targets can be managed with sustained arc rates of hundreds per second and have a far greater chance of running until exhaustion, or at least until the end of the process campaign.

AE Crystal LCC

The Crystal LCC detects arcs by looking for a precipitous increase in instantaneous plasma current. The Crystal drive inverter is turned off in about 100 nanosec. Voltage and current subside in less than 25 µsec. Arc handling turn-off duration is user-selectable, but is usually set at 100 µsec. The plasma is then re-ignited and returned to original set point by means of quickly ramping the output. Total duration of detection, handling, and recovery is usually less than 1 msec (the user can set it longer as in Figure 17). The following oscilloscope photo shows arc detection and shut down.

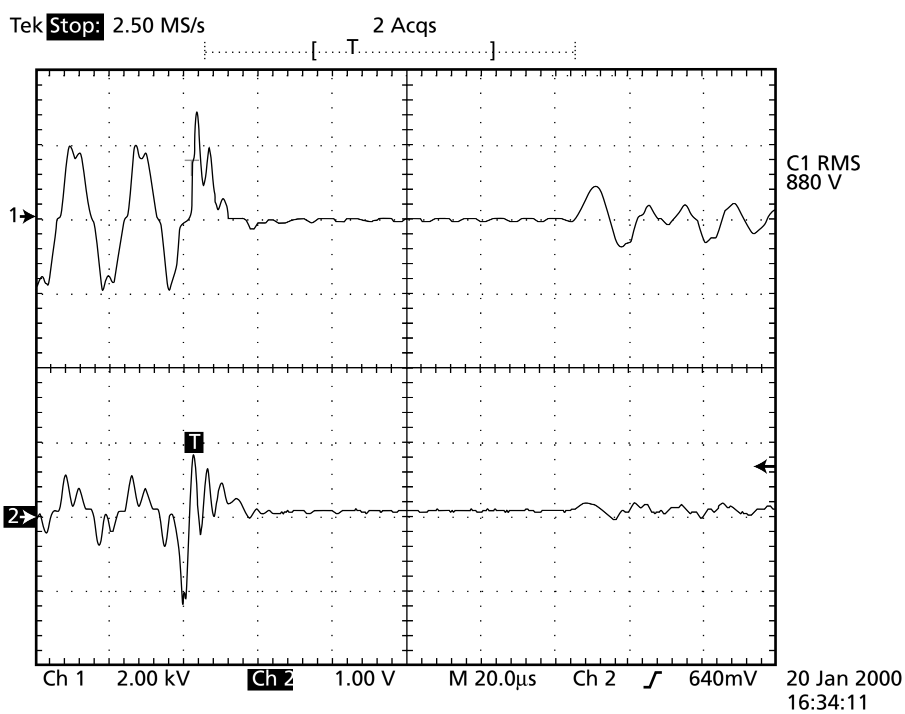

Figure 14. Crystal LCC arc response

Channel 1 is process voltage. Channel 2 is process current at 100 A per division. The following photo shows the Crystal LCC's arc recovery characteristic.

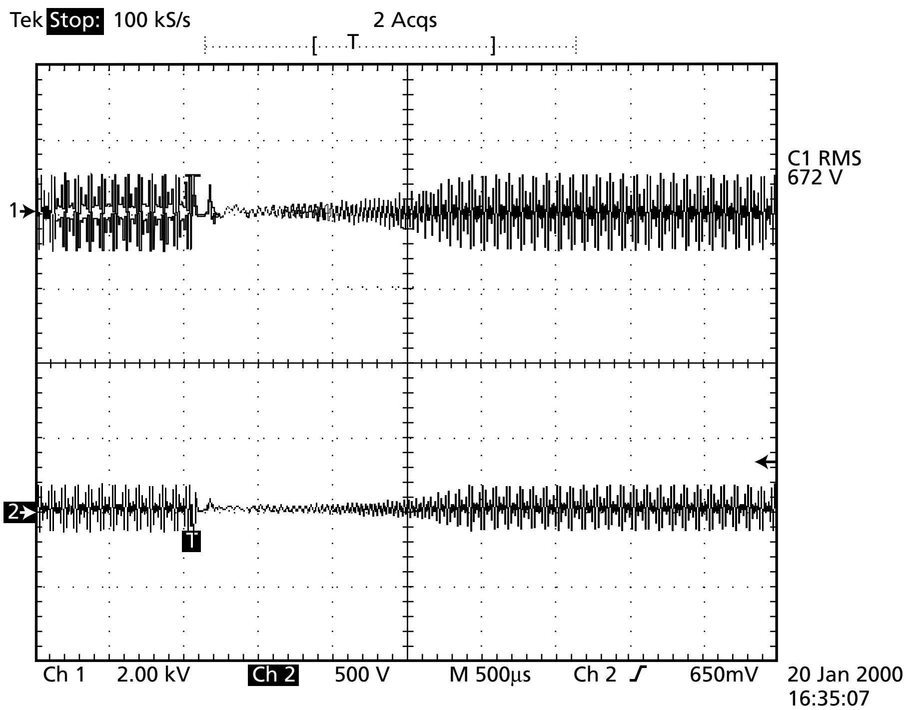

Figure 15. Crystal LCC arc recovery

The delivered arc energy has been measured at around 100 mJ at a power output of 100 kW. This is largely because the resonant network of the Crystal LCC was designed to store very little energy. In addition, measurements have shown that the vast majority of resonant circuit energy returns to the Crystal LCC topology, while handling an arc. It should also be noted that the current spike at the moment of arc is not cause for concern. Arc damage to targets and substrate is proportional to delivered arc energy, not arc current.

Plasma Ignition

Parallel Resonant

One of the under appreciated aspects of plasma process operation is the need to ignite the plasma from a cold start. Historically, this often requires the addition of special equipment connected to the process chamber for the purpose of ignition. This is because older power supplies could not produce high enough voltage to ignite the plasma. The reason for this can be seen in the parallel resonant gain curves of Figure 2. The gain curves deal with current, not voltage. Although parallel resonant supplies can produce high current gains (a very useful property for induction heating, but not particularly valuable as a plasma supply), maximum voltage is set by the drive voltage tolerance. The drive devices are usually IGBTs, which are especially unforgiving with regard to overvoltage stress. This means that for reliable operation, the voltage maximum is purposely kept relatively low.

AE Crystal LCC

The Crystal LCC, with its high open circuit voltage gain (seen in the curves of Figure 4), can produce extremely high voltages for ignition without any voltage stress on its devices (which operate at a constant voltage all the time). The maximum level is limited only to prevent damage to chamber insulators. On the highest tap, the maximum ignition voltage is up to 5300 V for the highest power Crystal LCC, should the process require it.

Conclusion

The introduction of new power supply designs offers the high-power market the modern performance characteristics previously enjoyed by the low-power industrial and semiconductor markets. As mentioned previously, some performance improvements offered by modern supply designs are superior plasma stability, vast breakthroughs in arc handling, and improved ignition.

The true value of power-supply improvements comes from gauging their impact on a coating plant in terms of both capital and operating costs. In addition, further reductions in coolant plumbing, pumping, and chillers are possible because of the low coolant flow requirements of the Crystal LCC.

Most significant is the potential capital cost reduction associated with stability-based improvements. Silicon processes provide an excellent example of capital cost reduction benefits. Since reactive silicon processes have proved most vexing to older technology, delivered power to those processes has been severely limited to well below the power supply capacity. Since silicon is a high-temperature material that could otherwise receive higher power with stable supplies, it is possible to eliminate some silicon cathode positions and make a shorter coater for the same product.

Operations-based cost reductions are even more significant. Elimination of scrap due to banding and spotting is the most obvious improvement. Process speed can be increased until affected by bottlenecks other than the power supplies. Higher supply voltages and improved arc handling allow the operation of thicker targets with a far greater probability of uninterrupted operation of those targets to exhaustion. In addition, systems using Crystal LCCs encounter fewer target management problems, which allows you to complete the campaign (process run) without having vent the entire coater. Improved efficiency leads to significant energy cost savings. In addition, the elimination of the aforementioned filters and other ancillary equipment lead to further operations savings, since this hardware has proven reliability problems.

Beyond these benefits, new technology offers the ability for a plant to change. Even processing plants that were originally intended to run one product forever occasionally need to implement unexpected changes at some point in their operating lifetime. Before the advent of new supply technology, when process stability was contingent on precise setup and tuning of supplies implementing such changes was a very risky venture. When this occurred, if at all, it usually involved, not only the coater owner, but also the coater OEM and the power supply OEM, all of whom were at least partially consumed with proprietary concerns.

Modern power supplies such as AE's Crystal LCC offer plant operators a high degree of process flexibility since they typically accommodate changes in process without requiring configuration changes. This, in turn, allows plant owners greater autonomy in configuring and running their operations.

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