System Design with Xenon Power Supplies

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Xenon lamps are used today in a number of applications, including medical endoscopy, dental curing and whitening, and video projection. Integrating xenon lamp power supplies, often called "ballasts," into a lighting system requires attention to a number of details. Unlike switching power supplies for low-voltage +5V and +/- 12V systems, xenon supplies cannot be simply dropped into a design and expected to work reliably. This is primarily due to the characteristics of the lamp itself. Xenon arc lamps require a high-voltage spike for lamp ignition followed by a boost voltage of 100 V. The plasma created within the lamp generates a large amount of heat that must be dissipated, and the system must limit the amount of electrical interference to external devices.

This application note covers some of the issues system designers need to consider when designing with xenon lamp power supplies.

Capacitance and Ignition

Probably the most distinctive characteristic of xenon lamps is the absence of a filament. Instead, an arc is formed between two electrodes that are surrounded by xenon gas. The fill pressure of the gas is typically 10 atmospheres, and the gap is 1.0 to 3.0 mm.

To ignite the lamp, an arc must be established between the two electrodes. The power supply has the job of generating a 25 KV voltage spike. This pulse lasts for only 10 ns and serves to bridge the gap between the electrodes. At this point the arc has been established, but is small and presents a fairly high impedance. The power supply then goes into a boost phase where approximately 100 V is applied to the lamp for 5 µs. This causes more current to flow in the arc, making it both thicker and lower impedance. The power supply then goes into a constant-current mode (sometimes constant-power) and supplies approximately 12 to 14 V. At this point the lamp acts like a zener diode with a fixed voltage drop and a low AC impedance.

One of the issues the system designer must address is the wiring from the high-voltage generation circuitry (the ignitor) to the lamp. First we will look at how the high-voltage pulse is created. Most xenon supplies are not isolated from the AC mains. One of the outputs is at mains potential while the high-voltage pulse is applied to the other. In the case of a negative-side ignition, the positive output remains still while the negative output pulses to -25 KV.

This pulse is generated with a simple voltage multiplier circuit. The output energy is finite and designed to drive a 10 pF load. The wiring on the negative side (in this case) must have high-voltage insulation, preferably 30 KV-rated silicone insulated wire. The positive-side wiring only requires enough insulation to prevent breakdown to chassis ground, which usually means standard 600 V wire is sufficient.

Here comes the important part: because the ignition pulse is finite energy, a 25 KV pulse into a 10 pF load will only give a 17.7 KV pulse into a 20 pF load. This means that as little as 1 pF of additional capacitance (above 10 pF) between the output leads will degrade the ignition pulse and cause hard starting of the lamp. This effect will not be obvious with new lamps, but lamps near the end of their lifetime tend to have the gap eroded away and require a slightly higher ignition pulse.

As mentioned above, the positive pulse is at mains potential. There is a relatively large amount of capacitance between the mains and earth ground. This means that capacitance between the negative lead and chassis is just as bad as capacitance between the negative and positive leads. The answer is to keep the negative lead away from the positive lead and away from chassis ground. A useful measurement during development is to measure the combined capacitance of the lamp, lamp fixture, and wiring. This can be done by connecting the positive lead to the chassis (at the supply end), then measuring the capacitance between the negative lead and chassis. This shows the combined lead-to-lead and lead-to-ground capacitance. A four-wire measurement is often required in order to resolve the small amount of capacitance.

Of course all of these discussions are reversed if the ignition pulse is on the positive lead of the output. Many manufacturers choose to use high-voltage wire for both output leads to allow for second-sourcing a power supply with either positive- or negative-side ignition pulses.

Heat and Airflow

The management of heat is often one of the major constraints in designing a new xenon light source. Almost all of the heat in the system will be generated in only two places: at the lamp and at the power supply. For a first-order approximation, it is fair to assume that the power supply is 66% efficient (worst case). This means that the total system power will be 150% of the lamp rating: 450 W for a 300 W lamp and 270 W for a 180 W lamp. In the case of the 180 W lamp, 90 W is dissipated by the power supply.

The method of removing heat from the lamp depends on the lamp; the problem is different for bubble lamps than for ceramic lamps. Bubble lamps tend to have most of the heat concentrated at the positive end of the quartz housing. This requires a high-velocity airflow past the tip because the conducting area is small. Ceramic lamps have the advantage that the heat is conducted through a metal contact at the rear of the lamp which can be connected to a heatsink. The larger surface area of the heatsink permits a lower air velocity to achieve the same cooling.

The power supply dissipates most of its heat through an integral heatsink to which two or more semiconductors are attached. The goal is to figure out a way to take cool air from the outside past the power supply, past the lamp, and then out of the box. Whether the air goes past the power supply first or the lamp first is a matter of thermal design. As a rule of thumb, the ceramic temperature on a ceramic lamp should not exceed 150ºC, and the power supply heatsink temperature should not exceed 90ºC. These numbers should be confirmed with the lamp and power supply manufacturers before system design is begun.

Three common mistakes in using air to cool light sources are high path resistance, poor cooling of ancillary components, and lack of confinement. Airflow through a system is not unlike current in a loop. The fan acts like a current source and forces air through the enclosure. The fan creates a certain pressure; the amount of air that flows depends on how much resistance it encounters along the way. If the route the air has to take is convoluted, or the inlet or outlet holes are too small, then the volume of air flowing will be small. Sometimes a designer will build a wonderful system with a large fan mounted on the side and straight-through airflow, but forget to make the outlet holes large enough. It is important to remember that the air must flow in a loop. Making the outlet holes too small is as bad as, for example, having a 1" diameter hole in front of a 3" fan.

The second mistake is to overlook the temperature of ancillary components not attached to a heat sink. All electrical components generate heat during operation. Power magnetics (inductors and transformers) and bulk capacitors in particular dissipate significant amounts of heat. Typically, the majority of the flow in a forcer-air cooling system is directed through intentional heat sinks. In a properly designed system, however, a portion of the cooling must be directed across other heat-dissipating components. It is important to monitor the temperature of these ancillary components to ensure they are being cooled adequately, thus operating within their temperature specifications.

Finally, the third most common mistake is lack of confinement resulting from failing to guide the airflow in a deterministic way.

Placing a fan at one end of the enclosure and outlet holes at the other end does not guarantee that the air will flow past the heatsinks as desired. In some designs the dimensions of internal dividers and positioning of inlet and outlet holes is sufficient to guide the air. Other times, particularly in large boxes, the air chooses the path of least resistance which is often around the heatsink, rather than past it. Confinement can be improved with the addition of simple Nomex barriers. Sometimes a single barrier at a critical location can reduce the lamp or power supply temperature by 10ºC. If the barrier must be in contact with a high temperature component, such as the lamp heatsink, then other materials are often required. Phenolic has the advantage of being fairly machinable, but can be costly for large pieces. High temperature thermoplastics are also used.

The most important thing to do is to characterize the system before going to production. Temperature measurements should be made on the lamp, lamp heatsink, and power supply heatsink. Ambient air temperature should be measured at the same time in order to maintain correlation between measurements taken at different times. It is not uncommon for the temperature in a room (and hence all the measurements) to increase by 5ºC when several pieces of test equipment are running at once. One of the tricky measurements is lamp temperature. If the thermocouple is attached to the lamp during ignition, it is likely that a 25 KV spike will travel down the thermocouple wires and damage the instrument. This problem is usually solved with quick-disconnect connectors on the thermocouple in question; the sensor is reconnected only after the lamp is lit.

EMI Considerations

EMI emissions testing is often the most intimidating part of system design. There is a continuous battle between product cost and EMI compliance. Although many volumes have been written on EMI compliance, these can be boiled down into two schools of thought:

- Do it now.
- Do it later.

Although these options may appear frivolous, they are in fact based on the two most common approaches.

The "do it now" school of thought assumes the worst and designs accordingly. A large line filter is used, ferrites are placed on wires going to the fan and peripheral circuitry, and gaps in the case are sealed with EMI gaskets or finger stock. One advantage to this method is that the product is likely to pass on first try (or with very little modification). The product development schedule is predictable, and the agony of fixing a non-complying product is absent. The disadvantages are that the product takes longer to develop and costs more. The increase in cost is because it is unknown ahead of time which of the EMI fixes are necessary, and it would take too much testing time to determine this at the test facility.

The "do it later" method results in a very different development process. EMI issues are not addressed until late in the development cycle when solid prototypes are available. No costly EMI measures are incorporated during system design. When testing is started, the product rarely passes on the first or even second try. Various fixes are added until the product meets the specifications, and then it is released to production. The most important advantage is that the product costs less because only the minimum number of EMI suppression components are added. Although the product cost may be less, the testing costs are always more, and these costs must be amortized across the expected product lifetime. The major disadvantage is that the development schedule become unpredictable: compliance may take between 1 week and 6 months. (This author is aware of a product that was in and out of testing for 18 months before the project was cancelled.)

Both methodologies are valid. The "do it now" proponents may gloat in the fact that they passed EMI testing on the first try and were first to market. But the "do it later" competitor may have the last laugh when they arrive later with a cheaper product. There is a continuum of approaches that balance the two extremes. It is important that management understand at the outset which approach they wish to adopt, and to accept the strengths and weaknesses of the chosen path. Regardless of the approach, it always helps to have a lamp or power supply manufacturer that is experienced in EMI issues and is available to offer their expertise.

Safety

Although there are many aspects of product safety, the primary concern in medical and dental xenon light sources is leakage current. Leakage current is the amount of current that flows in the ground wire returning to the wall outlet. The primary contributor to leakage current is the presence of Y-capacitors in the input EMI filter (figure 1). Larger capacitors make a better filter and in turn reduce EMI emissions.

Calculating the leakage current is fairly straightforward. The largest component of leakage current is 50/60 Hz line current flowing through the Y-capacitors to ground. The line neutral is at approximately at earth ground potential, so no current flows through this capacitor. The hot side of the line can have a potential of up to 265 VAC with respect to neutral, and hence with respect to ground. The current is simply 265 VAC divided by the capacitive reactance. The larger the value of capacitance, the higher the leakage current.

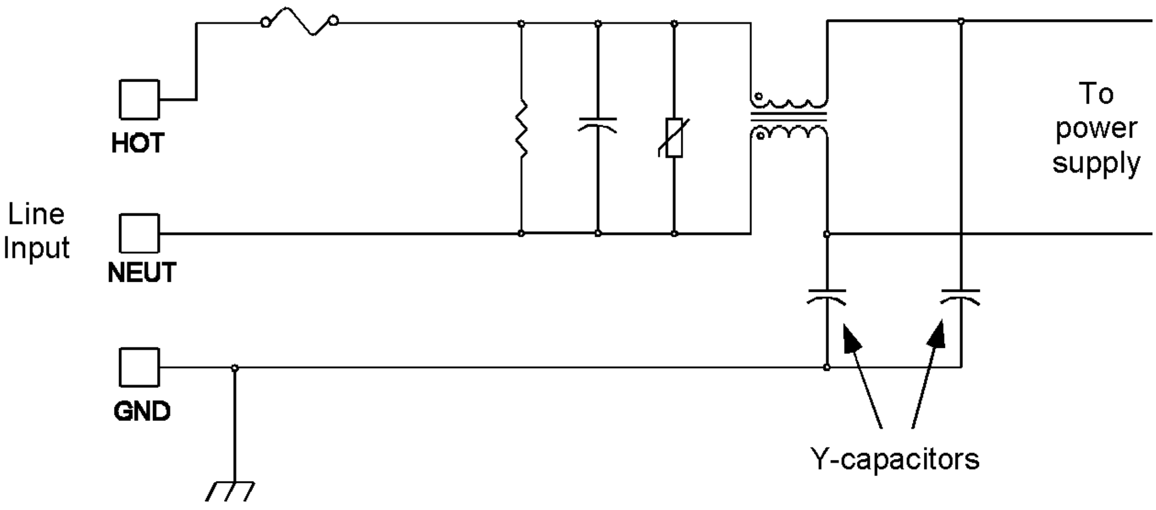

Figure 1 – Typical EMI input filter with Y-capacitors

How much leakage current is allowed? This is a complex question that depends on the end use of the product. We can outline some of the more common specifications here, but a definitive answer can only be obtained by reading the appropriate standard. Most industrial equipment is constrained by UL1950 which allows a leakage current of 3.5 mA (5.0 mA under certain circumstances). The old standard for medical products was UL544 which specified a leakage current of 100 μA. This standard has been supplanted by IEC 601 (EN 60601) internationally, or by the harmonized UL2601 standard in the U.S. The IEC 601 standard specifies a maximum leakage current of 500 μA at high line voltage. UL2601 reads the same, except for an entry under "North American deviations" that limits the current to 300 μA.

One of the issues a medical product manufacturer must address is whether to specify the leakage current as 100 or 300 µA. If the 100 µA limit is chosen, then the Y-capacitors will be smaller and the EMI levels will be higher. On the other hand, many hospitals in the U.S. have not read the latest standards and still test to the 100 µA limit. Some of these hospitals refuse to accept products rated at 300 µA, even though they comply with the UL medical standard. This EMI vs. leakage current tradeoff remains an important issue for manufacturers.

Hidden Costs

When the total system cost is considered, there are often good reasons for using a highly-integrated power supply rather than a bare-bones one. A long-time issue for switching power supplies is conducted emissions through the line cord. A good EMI line filter integrated into the supply can reduce the required size (and cost) of an external filter.

Auxiliary power is another place where there are several options for the system designer. A source of +12V is often needed to run fans and control electronics. If any of the circuitry attached to this supply can be touched (or nearly touched) by a user, then the auxiliary supply must have SELV isolation. SELV is the UL designation for Safety Extra Low Voltage. It means that the supply has 8 mm of isolation from any mains voltage and a 4 KV signal will not pass from the mains to the +12V output. If the supply is used for running fans, the extra cost of SELV isolation is not required. But if it is used to run control electronics, and those circuits have user-operated buttons or indicators, then SELV is required.

Some xenon lamp power supplies have built-in auxiliary supplies. Many, but not all, also have SELV isolation. There are two ways that are commonly used to provide +12V output: lamp-derived and independent supply. The lamp-derived auxiliary output counts on the fact that the lamp voltage is typically between 12 V and 14 V. A low-dropout regulator takes power from across the lamp output and drives a 2-pin connector. The disadvantage here is that the current to the lamp is reduced by the auxiliary load. For example, a 175 W lamp typically runs at a current of 14.0 Amps. If the system has two fans at 400 mA each, then the actual current to the lamp is only 13.2 Amps. This can be corrected by increasing the output current, but the lamp current is still dependent on load changes and unit-to-unit variations in the fans. Another disadvantage to this method is that when the lamp is not running, the auxiliary supply is off. If the supply shuts down the lamp in an overheating situation, then the fans also shut down.

Independent integrated supplies are usually a separate switching power supply that runs directly off the line. The +12V output is always present when power is applied, which is particularly useful if any control electronics are used to turn the lamp on and off. The output voltage is independent of lamp voltage, and can be SELV isolated. SELV isolation is impractical with lamp-derived supplies.

Sometimes a number of output voltages are required, such as +5V, +12V, and -12V. If the currents are more than a few milliamperes, then an additional switching supply is usually called for. It is very important to check for compatibility between any low voltage supplies and the lamp supply. Several low-cost power supplies use control circuitry that is susceptible to external transients. This is characterized by the supply shutting down whenever the lamp ignites. This is a hard shutdown and requires cycling power before the supply will recover.

Troubleshooting

The most common complaint when a system isn't working is "the lamp won't light." There are a number of subtle problems that can cause the lamp not to ignite. When a situation like this is encountered, the first thing to do is to look inside the lamp. The best way to do this is from an angle to the side with safety glasses; never look at the lamp along the optical axis. There will be four possible results:

1) There is no visible arc in the lamp.

2) There is a small blue arc between the electrodes.

3) There is a bright white flash (difficult to look at).

4) The lamp turns on and runs.

Case 1 means that the energy from the ignitor isn't making it to the lamp. First determine whether the ignitor is working. It should be arcing at a regular rate with an audible click. There are two types of ignitors in common use: one tends to generate one pulse per second (at 120 VAC) and the other generates about 10 pulses per second (machine-gun type ignitor). If the clicking is not present, then it is likely that the output is shorted, there is no AC present, or the enable input is not true (not applicable if auto-run jumper installed).

If the audible clicks are present, look for things that may steal energy from the ignitor. Some examples are output lead shorted to ground, low-voltage insulation on the output wires, or excessive capacitance in the output wiring and lamp fixture. Check to see whether the supply has a negative-side or positive-side ignitor. If the ignitor is negative-side and the product has low-voltage wiring or a temperature sensor connected to this side, then ignitor energy will be lost.

If an alternate discharge path is present, arcing can often be heard or seen where the wiring comes too close to chassis components. The smell of ozone is often associated with this fault. The location of the arcing can sometimes be found by extinguishing the lights in the room and looking carefully around the power supply, output wiring, and lamp housing.

Case 2 indicates that a high resistance is present in the output wiring. For example, suppose the wiring has broken inside of a crimp connector. The high-voltage ignition pulse has no problem jumping the gap in the wire and the gap in the lamp, but the open circuit prevents any DC current from flowing in the lamp.

The presence of a small blue arc without the lamp starting can sometimes be associated with old or damaged lamps. These lamps have a gap that is short enough for the ignition pulse to cross, but too long to establish a stable arc.

Case 3 is an indication that the ignition pulse has started the lamp, and the boost circuit has discharged (causing the white flash), but the rest of the supply is not sustaining a DC current. This problem is more complex to diagnose, but often indicates that stray wiring is allowing ignition energy to get back into the control circuitry of the supply. This causes the pulse width modulator chip to shut down, which extinguishes the lamp. The PWM then restarts, enables the ignitor, and the process repeats itself. Problems in this category often require assistance from the power supply manufacturer.