

High Voltage Power Supplies for Analytical Instrumentation

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ABSTRACT

Power supply requirements for Analytical Instrumentation are as varied as the applications themselves. Power supply voltages ranging from 3 volts to 300,000 volts can be found within a given instrument. While most voltage requirements can be satisfied with "off the shelf" products, the high voltage requirements are usually addressed by a custom design for a specific application. Custom designed high voltage power supplies can be found in instruments for spectroscopy, capillary electrophoresis, mass spectrometry, electrospray, lasers, spectrometers, X-ray diffraction, X-ray fluorescence, and many other analytical imaging and process applications.

Each application of High Voltage Power will require careful attention to critical variables. Voltage ripple, long and short term stability, repeatability and accuracy are important factors in the consideration of reliable scientific data. Also, as analytical instrumentation finds its way into production process control, reliability and quality are equally important in the considerations for high voltage power supply specification.

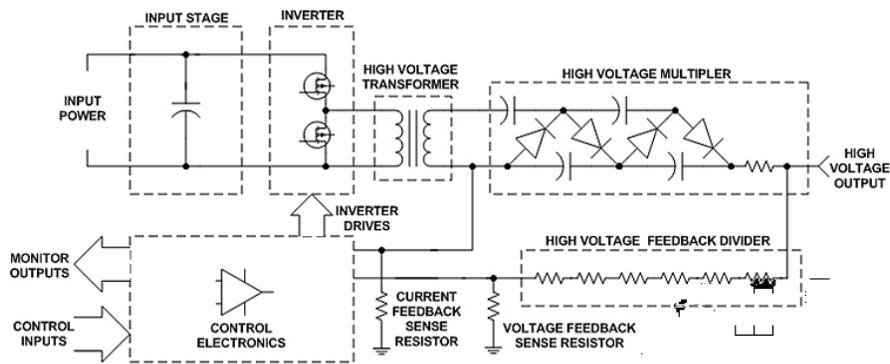
Specific performance concerns, technology advances and application information are presented for the designer, specifier and user of high voltage power supplies for analytical instrumentation.

INTRODUCTION

High voltage power supplies are a key component in many analytical instruments. By the nature of analytical applications, test equipment, methods and data must show consistent results. The high voltage power supply, being a critical component within the instrument, must perform consistently also. The high voltage power supply has unique concerns which differentiate it from conventional power supply requirements. By understanding these concerns, the designer and user of Analytical Instrumentation can gain beneficial knowledge.

BASIC HIGH VOLTAGE POWER SUPPLY

Figure 1 shows the basic building blocks of most high voltage power supplies. The Power Input stage provides conditioning of the input power source. The input power source may have a wide range of input voltage characteristics. AC sources of 50Hz to 400Hz at <24Vac to 480Vac are common. DC sources ranging from 5Vdc to 300Vdc can also be found. The power stage can provide rectification and filtering for AC signals, filtering for DC signals and circuit protection. Also, auxiliary power sources to power the high voltage power supply control circuits are typically part of the power input stage responsibilities. It is critical for the instrument designer to understand the input circuit configurations. The power input requirements will affect overall instrument design, customer requirements, and even regulatory requirements.



BASIC HIGH VOLTAGE POWER SUPPLY
FIG. 1

The output of the power input conditioning stage is typically a DC voltage source. This DC voltage provides the energy source for the Inverter stage. The Inverter stage converts the DC source to a high frequency AC signal. Many different inverter topologies exist for power supplies. However, the high voltage power supply has a few factors which may dictate the best approach.

INVERTER CONSIDERATIONS

Typically, the Inverter generates a high frequency AC signal which is stepped up by the HV transformer. The reason for the high frequency generation is to provide high performance operation with reduced size of magnetics and energy storage capacitors. A problem is created when a transformer with a high step up ratio is coupled to a high frequency inverter. The high step up ratio reflects a parasitic capacitance across the primary of the high voltage transformer. This is reflected at a $(N_{sec}:N_{pri})^2$ function. This large parasitic capacitor which appears across the primary of the transformer must be isolated from the Inverter switching devices. If not, abnormally high pulse currents will be present in the Inverter.

Another parameter which is common to high voltage power supplies is a wide range of load operations. Due to the presence of high voltage, insulation breakdown, i.e. tube arcing, is commonplace. The inverter robustness and control loop characteristics must account for virtually any combination of open circuit, short circuit and operating load conditions.

In addition to wide load variations, virtually all analytical instruments need to resolve very low signal levels and contain high gain circuitry. Noise sources, such as power supply inverters must be considered. The Inverter can be a likely source of noise due to the high DI/Dt and DV/Dt created when the Inverter power devices switch on and off. The best approach to reduce the noise source is to have a resonant switching topology. Low output ripple, low input power source ripple and good shielding practices are also important. All of these concerns, as well as reliability and cost, must be addressed in the High Voltage Power Supply Inverter topology.

TRANSFORMER CONSIDERATIONS

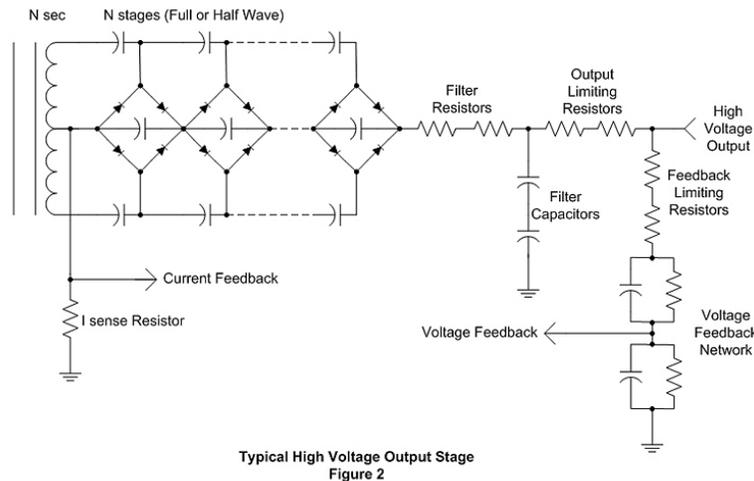
The High Voltage Transformer is, historically, where most of the "Black Magic" occurs. In reality, there is no magic. Complete understanding of magnetics design must be coupled with intense material and process control.

Much of the specific expertise involves managing the high number of secondary turns, and the high peak secondary voltage. Due to these two factors, core geometry, insulation methods and winding techniques

are quite different than conventional transformer designs. Some areas of concern are: volts/turn ratings of the secondary wire, layer to layer insulating ratings, insulating material dissipation factor, winding geometry as it is concerned with parasitic secondary capacitance and leakage flux, impregnation of insulating varnish to winding layers, corona level and virtually all other conventional concerns such as thermal margins, and overall cost.

HIGH VOLTAGE OUTPUT STAGE

The high voltage output stage is responsible for rectification and filtering of the high frequency AC signal supplied by the high voltage transformer secondary (Figure 2). This rectification and filtering process invariably utilizes high voltage diodes and high voltage capacitors. However, the configuration of the components varies widely. For low power outputs, conventional voltage multipliers are used. For higher power, modified voltage multipliers and various transformer techniques can be successful. The high voltage output stage also provides feedback and monitoring signals which will be processed by the power supply control circuits. All of these components are typically insulated from ground level to prevent arc over. The insulation materials vary widely, but typical materials are: air, SF₆, insulating oil, solid encapsulants (RTV, epoxy, etc.). The insulating material selection and process control may be the most important aspect of a reliable high voltage design.



CONTROL CIRCUITRY

Control circuits are the glue to keep all of the power stages working together. Circuit complexity can range from one analog I.C. to a large number of I.C.s and even a microprocessor controlling and monitoring all aspects of the high voltage power. However, the basic requirement which every control circuit must meet is to precisely regulate the output voltage and current as load, input power, and command requirements dictate. This is best accomplished by a feedback control loop. Figure 3 shows how feedback signals can be used to regulate the output of the power supply. Conventional regulation of voltage and current can be achieved by monitoring the output voltage and current respectively. This is compared to a desired (reference) output signal. The difference (error) between the feedback and reference will cause a change in the inverter control device. This will then result in a change of power delivered to the output circuits.

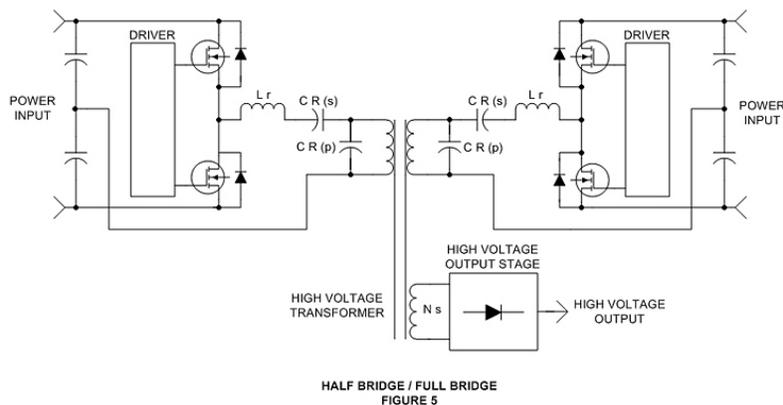
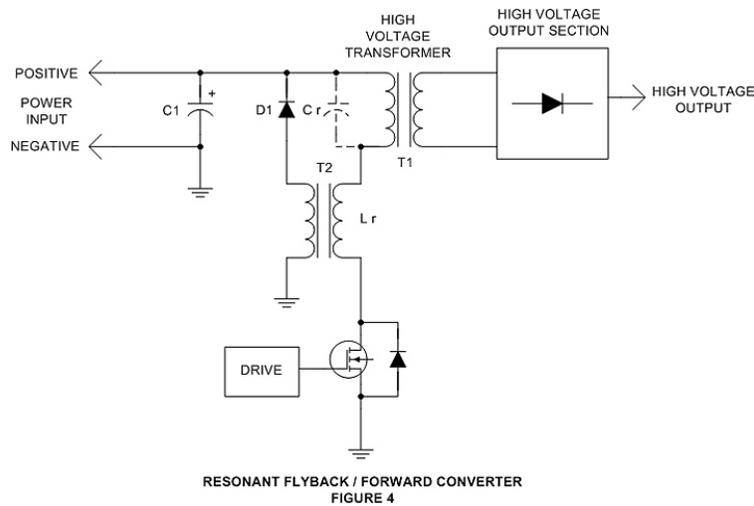
In addition to the voltage and current regulation, other parameters can be precisely regulated. Controlling output power is easily accomplished by an $(X)(Y) = Z$ function, where $(V)(I) = W$, and comparing it to the desired output power reference. Indeed, any variable found within Ohm's law can be regulated, (resistance, voltage, current and power). In addition, end process parameters can be regulated if they are affected by the high voltage power supply (i.e. X-ray output, flow rates, etc.).

INVERTER TOPOLOGIES

As mentioned above, there are a wide variety of Inverter topologies existing today. However, the choice of Inverter topologies for a high voltage power supply may be governed by two factors:

- Must isolate reflected parasitic capacitance
- Must be low noise

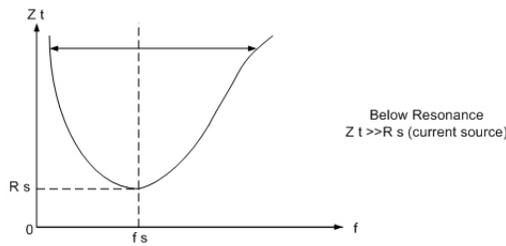
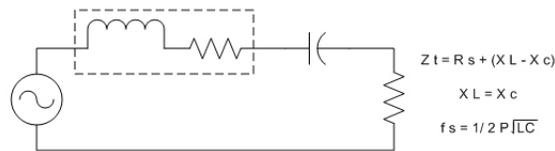
Luckily, there is one general approach which meets both requirements. This approach is resonant power conversion. Resonant topologies utilize a resonant tank circuit for the generation of the high frequency source. Figure 4 and 5 show two implementations of the resonant approach. Both successfully isolate the reflected capacitance by a series inductor. In some cases, the reflected capacitance (C_R), and the series inductor (L_R) comprise the tank circuit. This is known as a series resonant/parallel loaded topology. In other cases, a capacitor is connected in series with the inductor to form a series resonant/series loaded topology.



The two approaches have two distinct differences. The parallel loaded topology more closely resembles a voltage source; while the series loaded topology resembles a current source. Each has advantages, but typically, the parallel loaded topology is used in low power applications, and the series loaded topology is used in high power operations. Many reasons exist for this differentiation of use with power level, but

there are a few dictating reasons why each cannot be used in the others domain. To understand this we need to visualize the reflected capacitor and what happens to this capacitor during an output short circuit. This is of primary importance because under a short circuit condition the parasitic capacitance is reduced by the reflected secondary load, in this case zero ohms. In the low power application, the series inductor is of a relatively high impedance, (due to its VA requirements), and provides Vt/L current limiting for the inverter switching devices.

In the high power, the series inductor is of substantially lower impedance, and does not provide inherent current limiting. For this reason, a series loaded circuit is used. It can be seen by Figure 6, that a series loaded circuit, when operated outside its resonant tank frequency, resembles a current source inherently limiting the current capabilities and thereby protecting the switching devices. (Figure 6)



SERIES RESONANCE
FIGURE 6

Still other reasons exist why a series loaded circuit cannot be used at low power. It can be seen that the series capacitor will support a voltage dictated by the Q of the resonant circuit and the applied voltage. In all cases, this voltage is seen across the total circuit capacitance, the series capacitor, and the parasitic capacitor. In the low power application the ratio of the series C to the parallel C is very high (again due to the VA requirements of the tank). This effectively creates a voltage divider, with most of the voltage appearing across the series C. This results in a significantly lower voltage applied to the transformer, thereby limiting high secondary voltages. If higher turns are added, more reflected capacitance is created and eventually no additional secondary volts can be generated.

OUTPUT STABILITY, REGULATION AND REPEATABILITY

As stated previously, the importance of consistent results is paramount in the analytical process. The high voltage power supply must be a source of stable and repeatable performance. Variations in the output voltage and current will usually have direct effects on the end results and therefore must be understood as a source of error. In high voltage power supplies, the voltage references that are used to program the desired output can be eliminated as a source of significant error by the use of highly stable voltage reference I.C.s. Typical specifications of better than 5ppm/°C are routine. Similarly, analog I.C.s (op amps, A/D, D/A's, etc.) can be eliminated as a significant source of error by careful selection of the devices. [1]

There remains one component, unique to high voltage power supplies, which will be the major source of stability errors: the high voltage feedback divider. As seen in Figure 2, the high voltage feedback divider consists of a resistive divider network. This network will divide the output voltage to a level low enough to be processed by the control circuits (i.e. <10vdc).>

The problem of stability in this network results from the large resistance of the feedback resistors. Values of >100 megohms are common. (This is to reduce power dissipation in the circuit and reduce the effects of temperature change due to self heating). The large resistance and the high voltage rating requires unique technology specific to high voltage resistors. The unique high voltage resistor must be "paired" with a low value resistor to insure ratio tracking under changes of temperature, voltage, humidity and time.

In addition, the high value of resistance in the feedback network means a susceptibility to very low current interference. It can be seen that currents as low as 1×10^{-9} amps will result in >100ppm errors. Therefore, corona current effects must seriously be considered in the design of the resistor and the resistor feedback network. Also, since much of the resistor technology is based on a ceramic core or substrate, piezoelectric effects must also be considered. It can be demonstrated that vibrating a high voltage power supply during operation will impose a signal, related to the vibration frequency, on the output of the power supply.

AUXILIARY OUTPUTS

In many applications of high voltage, additional power sources are required for the instrument. In many cases, these auxiliary power sources work in conjunction with the high voltage power supply. Such examples are: Filament (heater) power supplies as found in every X-ray tube, bias (grid) control supplies, focus power supplies, and low voltage power requirements for other related control circuitry.

The instrument designer may choose to have one vendor provide all of the power supply requirements. This is very common in the high voltage area due to the expertise required when dealing with related high voltage circuits (i.e. filament isolation requirements). For the high voltage power supply designer this means an expertise in virtually all aspects of power conversion technology, not just high voltage power supplies. For example, it is not uncommon to find filament power supplies providing greater than 100 amps at 20 volts. In addition, this output circuitry may need isolation as high as 100,000 volts. Even motor control expertise is used in new high voltage technology.

CONCLUSION

This paper presented an overview of areas that are specific to the high voltage power supply. The high voltage power supply has unique concerns which differentiate it from standard off the shelf products. The designer, specifier and user of high voltage power must be aware of these concerns, in order to insure the best possible results. The technological advances in power conversion are occurring at such rapid rates that is it difficult for an instrument designer to undertake full responsibility of the high voltage power supply design. This responsibility, therefore, must be shared by the supplier of the high voltage power supply and the instrument designer.

As discussed in this paper, advanced power conversion technology, components, materials, and process are required for reliable high voltage design. In addition, the safety aspects of high voltage use require important attention. High voltage sources can be lethal. The novice user of high voltage should be educated on the dangers involved. A general guideline for safety practices is found in IEEE standard 510-1983 "Recommended Practices for Safety in High Voltage and High Power Testing [4]".

REFERENCES:

- [1] Precision Monolithics Inc. (PMI), "Analog I.C. Data Book, vol. 10.
- [2] D. Chambers and C. Scapellati, "How to Specify Today's High Voltage Power Supplies", Electronic Products Magazine, March 1994.
- [3] D. Chambers and C. Scapellati, "New High Frequency, High Voltage Power Supplies for Microwave Heating Applications", Proceedings of the 29th Microwave Power Symposium, July 1994.
- [4] IEEE Standard 510-1983, IEEE Recommended Practices for Safety on High voltage and High Power.