Custom Engineering HV Power Supplies for High Performance Applications

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High voltage power supplies (HVPS) are required in a multiplicity of configurations and capabilities. Dimensions, type of enclosure, weight, input and outputs, thermal and electromagnetic interference (EMI) shielding, cooling method, connectors, etc., can vary with each application. While some manufacturers offer standard products that can be sold "off-the-shelf," HVPS applications most often mandate customization. Depending on the specifications, regulatory requirements, development schedule of the OEM[1], suitability of an existing platform, customer changes, and other factors, the process can take as long as a year to complete. A "designed from scratch" HVPS will take even longer.

Excelitas Technologies designs and manufactures high performance, high reliability power supplies for the unique requirements of a particular customer and application. Products developed by the company provide power levels to 100kW, with output voltages that range from 300 V to 750 kV. Excelitas power supplies are customized for specific applications, with dozens of new models being developed each year. This paper discusses some of the design and performance parameters that must be accommodated in engineering to design and produce a HVPS.

Engineering Considerations in Designing an HVPS

HVPS belong to a diverse family of devices that provide electrical power to electronic circuitry. Types include AC to DC power supplies, DC to DC converters, and controlled current power supplies. Virtually all new HVPS are designed using switch mode technology, in order to achieve high performance while keeping the size small and costs low. The list of switch mode topologies is long and each has performance advantages in certain areas or applications. It should also be noted that in many cases, the HVPS needs to provide several outputs.

Variations also exist in terms of how the power supply is packaged, with bare circuit boards, modules, open frames, enclosed frames, and rack mounts being typical variations.

[1] OEM = Original Equipment Manufacturer

Large HVPS systems may be housed in cabinets. Figure 1 depicts various modular HVPS supplies and two larger rack-mounted units.

Figure 1. Excelitas Modular and Rack-Mounted High Voltage Power Supplies

The choice of insulation system in a HVPS is usually driven by the output voltage and output power as well as the packaging. Typical insulation systems are based on air, dielectric oil, epoxy, RTV Silicone Rubber and Sulfur Hexafluoride (SF_6). The method of cooling is a factor as well, the choices often coming down to air, water or oil, depending on the platform design, the amount of heat to be dissipated, the output voltage, and installation infrastructure considerations. Figure 2(a) on the next page is a photograph of an RTV Silicone Rubber filled housing which encases an Excelitas Medical X-ray power supply and Figure 2(b) is an oil filled housing containing an Excelitas HV supply. Then, there are the particular features required by the application, such as power factor correction; number and adjustability of outputs; and the user interface or control. Typical controls include local front panel (analog or digital), electrical interface including analog and digital signals as well as computer interfaces including USB, Ethernet, RS232 and GPIB.

Figure 2(a): Potted HV Encasement

Figure 2(b): Oil filled HV Encasement

For low and medium voltage requirements, an off-the-shelf power supply can sometimes meet the needs of the application. On the other hand, high voltage power requirements almost always call for a unique solution, primarily because an existing power supply can seldom be found to satisfy the particular combination of specifications governing performance, packaging, cooling, and physical dimensions. Safety and risk reduction concerns also play a role. For example, designed-in protection from load arcing, EMI effects, and drops in input line voltage ensure equipment integrity, while design measures, such as interlock circuitry, low storage of energy due to high frequency operation, and control circuit regulation of the output, are intended to protect personnel, as well as the equipment.

The definition of “high voltage” varies depending on the context. Safety agencies reviewing electronic circuits generally define greater than 48 V as high voltage while the National Electric Code (NEC) specifies “greater than 600 volts”. Sometimes an arbitrary level such as greater than or equal to 1 kV may be considered high voltage. For the purposes of this paper, Excelitas demonstrates High Voltage products ranging from 300 V to 750 kV.

Despite the dissimilarities in design and performance, HVPS are generically configured as shown in Figure 3, consisting of an EMI filter, power factor correction (PFC) circuitry, rectifier, inverter, high voltage transformer, multiplier/rectifier-filter, high voltage divider, and feedback control system. How these components are configured in the circuitry depends on the type of HVPS and the topology approach taken by the design engineer in meeting the specifications. The input voltage can be either AC or DC, with lower power units sometimes employing DC (up to 48 Vdc) and higher power supplies designed for AC (115 Vac to 480 Vac)[2] or higher voltage DC (200 Vdc to 385 Vdc).

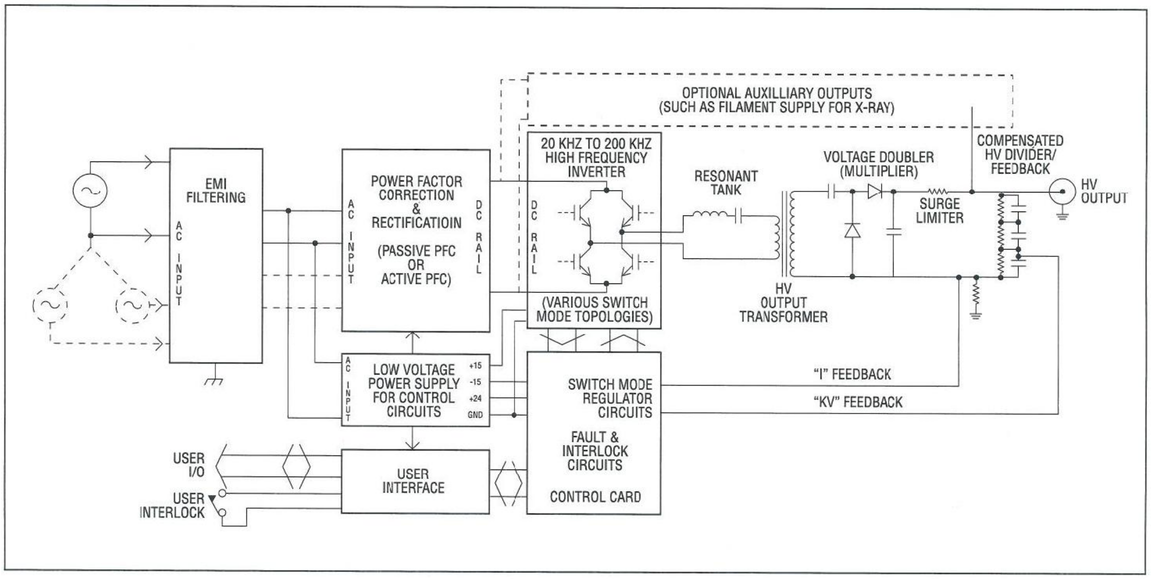

Figure 3. Block Diagram of a typical HVPS

As shown in Figure 3, input power is initially fed through an EMI filter and a rectifier stage to produce DC (by converting the input, if AC) and to filter out spurious noise. The rectifier also incorporates circuitry for power factor correction to minimize the phase angle, between the current and voltage waveforms for achieving a good power factor (real power divided by apparent power) greater than 0.84 and even as high as 0.99. Power factor correction (PFC) can be either *passive* or *active*. Passive circuitry, which is the technique generally preferred for high power units, consists of an inductor and capacitor network, and can often produce a power factor as high as 0.94 when measured

[2] The most common DC input voltages are 12 and 24 Vdc. AC voltages often depend on the country. 115/230 Vac, 60 Hz, for example, is the standard in the U.S., while the standard for most of Europe is 240 Vac, 50 Hz. Line voltage in Asian countries differs from both the U.S. and Europe. Power supplies can also be designed to accommodate a range of input voltage.

at full power. Active PFC can produce a power factor in excess of 0.98 over the full range of power output of the HVPS. CE standards enacted by the European Union, for instance, may apply in terms of harmonic content for some applications which are often met by use of an active PFC. An additional benefit of active PFC is the fact that a regulated DC rail results, often making the line regulation of the HVPS so good as to make it virtually immeasurable. Passive circuitry will produce a DC rail with a value dependent upon the magnitude of the AC line. Excelitas is able to engineer both single-phase and three-phase active power factor correction, as well as passive PFC.

Referring again to Figure 3, the resulting DC voltage output from the filter is applied to a resonant inverter, which then produces a high frequency AC signal. The inverter drives the primary windings of the high voltage “step up” transformer, the next stage in the process. The inverter can represent a formidable aspect of the power supply design, in that particular care must be taken to ensure high reliability and efficiency and to achieve the desired degree of margin with regard to component rating.[3]

Though the signal flow and the stages shown in Figure 3 are well understood, the actual topologies can be complicated and challenging to the engineer in creating a stable power supply output that meets the requirements of the customer and the application. The transformer, for instance, involves careful consideration of such factors as the core geometry, the number of primary and secondary turns, how the turns are wound, and the type and method of layer-to-layer insulation. It is here that problems can occur in terms of capacitance, insulation breakdown, thermal degradation and other undesirable conditions. As with the inverter stage, extensive engineering experience and the application of “tried and true” methods are essential for a viable design.

The next stage is the high voltage multiplier, which consists of a network of high voltage diodes and capacitors for rectifying, filtering, and multiplying the transformer voltage. The design process involves circuit analysis, prototyping, and testing to ensure the

[3] Margin can be defined as the difference between the maximum capability of a component and the actual “use” requirement of a circuit. Thus, the transistor rated for 1000 volts and installed in a 600 volt system would have a margin of 400 volts.

desired results. The circuitry must be protected from the high energy released when load capacitors are discharged (voltage reversal); and, in general, the power supply must be able to withstand both high current and large voltage transients. The design of a HVPS for powering an X-ray tube is an example of the circuit protection required, in that the transient effects of arcing must be tolerated by the HVPS while it manages the overall system's arc response.

The final stage, for most requirements, is a compensated high voltage divider with a feedback loop. The divider requires careful design to achieve the necessary transient response, limit overshoot, and perform satisfactorily during normal turn-on and turn-off operation. The basic premise is for the AC division ratio to be equal to the DC division ratio of the feedback divider so that the HVPS will accurately regulate during transient conditions (HV turn on, turn off, load discharge, arcing). Also it is very important that a properly designed high voltage divider allows for an accurate high-voltage monitor that will faithfully indicate what is happening at the high-voltage output in real time.

As shown in Figure 3, the control circuit incorporates an auxiliary low-voltage power supply, called a "housekeeping" supply, for running control circuits (regulator, fault logic, remote control, etc.) When needed, additional functionality can be incorporated into the HVPS design. An example is the "Omniblock," a complete X-ray source that incorporates the X-ray tube and its cooling system with the HVPS into a single compact enclosure.

HVPS Applications for Excelitas

Because of the ranges of voltage and power available from Excelitas, power supplies can meet the requirements of a number of market segments and be incorporated in a wide variety of OEM equipment. Table 1 provides a partial listing of applications and products.

Table 1

Market Segments and Representative End Uses For HVPS	
Market Segments/Applications	**Representative End Uses**
Analytical/Laboratory Equipment	Chemical/Element Analysis
	Electron Microscopy
	Mass Spectrometry
	Microfluidics
	UV Spectroscopy
	X-Ray Fluorescence, X-Ray Diffraction
Industrial X-Ray Inspection/NDT	Microfocus and Nanofocus Inspection of PCBs, Flex Circuits, and Components
	Inspection of Fabricated Parts and Welds
	Inspection of Ceramics and Plastics (Structure, Alignment, Porosity, etc.)
Materials Processing	Air/Water Purification
	Chemical Processing
	Food Inspection
	Ink Processing
	Metalworking and Fabrication
	Pharmaceutical Processing
Medical (Imaging)	Bone Densitometry
	CT Scanning
	Gamma Camera Imaging
	Mammography
	MRI Scanning
	PET Scanning
Medical (Treatment)	Dermatology
	Lithotripsy
	Ophthalmology
	Radiation Oncology
Security	Baggage X-Ray Screening
	Explosive Detection (EDS): Automated In-Line and Check Point Systems
	Explosive Trace Detection (ETD)

Market Segments and Representative End Uses For HVPS (cont'd.)	
Market Segments/Applications	**Representative End Uses**
Semiconductor Manufacturing	Electron Beam Lithography
	Electrostatic Coating
	Ion Beam Implantation
	Physical/Chemical Vapor Deposition
	Instrumentation
Government/Defense	Avionics Displays
	Secured Communications
	Electronic Countermeasures
	Flight Simulation
	RF Amplification and Microwave Heating with Klystrons/ Magnetrons
	Weaponry: Laser Guidance and Plasma Propulsion Systems
	Radar
	Night Vision
	Laser Ranging
	CRT

Certain products "cross the line" with regard to market segments. HVPS, for instance, are used to power lasers for such purposes as medical treatment, optical inspection, precision X-Y platform alignment, and non-contact welding. X-ray inspection systems, which also incorporate HVPS (the tube and power supply are sometimes packaged together as a product), are used for diverse operations ranging from baggage screening in airports to a host of industrial non-destructive testing applications. Excelitas also designs and manufactures capacitor charging power supplies for pulsed power applications, in particular, lasers and flash lamps.

Designing and Developing a Excelitas Power Supply

As stated previously, the process of custom designing and manufacturing a HVPS can take as long as a year. OEM customers usually do not want a "designed-from-scratch" power supply, and look to an existing platform technology as a proven, cost-effective starting point for a new product. In most instances, an off-the-shelf power supply cannot be used because of the uniqueness of the design and performance requirements.

In order to meet the development schedule of the OEM system in which the HVPS will be incorporated, initial key specifications and related details should be provided to Excelitas by the OEM system designer as soon as possible in the development process. ("Related details" can include non-specification requirements in terms of materials, manufacturing process, testing, prototype construction, approved vendors, documentation, etc.) In fact, early participation by Excelitas can not only smooth and expedite design and development, but can also enable Excelitas engineering to work with the customer to optimize the performance and physical specifications (size, weight, type of enclosure, method of cooling, etc.) for the power supply.

In the initial phases of a custom design effort, Excelitas prefers to visit the customer site to see the current state of the OEM design and to review expectations that may not be reflected in the specification. In fact, in most instances, however detailed the specification may be, not all of the relevant aspects of the design and performance requirements are likely to have been captured. Visits by Excelitas to the OEM should include, as a minimum, the project leader and design engineers assigned to the effort.

Routine technical and status discussions between OEM system designers and Excelitas benefit the customer in terms of schedule, product quality, and cost. Such discussions are normally conducted over the phone, but may entail visits, off-site meetings, and internet sessions. From the interaction between Excelitas personnel and the customer, a conceptual design evolves that accommodates the requirements of the OEM, while eliminating (or at least minimizing) project delays and ensuring minimal high voltage risk to equipment and personnel as the process evolves. Project efficiency is also enhanced because resources (personnel, facility, components, materials, etc.) can be allocated and schedules established for cost-effectively managing the project.

It is important to realize that certain specifications or parameters dictate or define the design approach. Also there usually are a set of specification tradeoffs that occur between, say, three parameters where in order to optimize the most important one, the others become more difficult, therefore requiring more material or greater size to achieve them. It is in these tradeoff decisions that Excelitas personnel can be particularly helpful to the OEM, avoiding tight specifications that may not be required and might represent an unnecessary cost to the customer. For DC power supplies, an example of this is output ripple vs. stored energy vs. transient response/settling. Very low output ripple can be achieved by adding more output capacitance, but this will increase the stored energy in the power supply and potentially be more damaging to the load connected to the power supply. Alternatively, lower ripple can be achieved by higher switching frequencies which may increase power dissipation or require more expensive semiconductor devices. Understanding the tradeoffs helps optimize the design for the OEM application.

Similarly there are specification and design tradeoffs in capacitor charging applications. Charge rate usually trades off against accuracy and repeatability. Faster charge rates enable higher repetition rates, which increases output power for a given load capacitor which may increase size and cost. Additionally, it is important to understand the nature of the discharge characteristic in order to determine the peak or instantaneous power level, which may be a more important design specification than the average power output required.

Why Excelitas?

Excelitas products are found in applications where there is no room for error or failure, such as medical treatment (lasers and other pulsed power products), medical CT, X-ray inspection, electron and mass spectrometry, and ion beam implantation. For these applications, and others, precision and reliability — for the HVPS, as well as the OEM product — are paramount. Beyond our history of high voltage experience, which dates back to 1931, our deep portfolio of enabling technologies and the broad range of applications and markets we serve, it is the strength of Excelitas' 3000+ employees across the globe that deliver value to our customers on a daily basis. Excelitas' core values – Integrity, Customer Focus, Continuous Improvement, Teamwork, and Organizational Agility - are the foundations that guide all of our actions. We are committed to enabling our OEM customers' success in their markets and applications by supplying innovative, customized power systems, optoelectronics and advanced electronic systems utilizing innovative, high-performance, market-driven technology solutions.