

HIGH VOLTAGE REFERENCE MANUAL

7/09 REV.2

TABLE OF CONTENTS

SECTION 1

Frequently Asked Questions

ARC/SHORT CIRCUIT	1
INTERFACING	1
SAFETY	2
TECHNOLOGY/TERMINOLOGY	3
USAGE/APPLICATION	6

SECTION 2

Application Notes

AN-01	
WHAT DO YOU MEAN; THE OUTPUT IS "GROUND REFERENCED"?	8
AN-02	
"GROUND IS GROUND", RIGHT?	
WHAT YOU NEED TO KNOW	8
AN-03	
WHEN OVER SPECIFYING A POWER SUPPLY CAN BE A BAD THING	8
AN-04	
WHY SIGNAL TO NOISE RATIOS ARE IMPORTANT IN PROGRAMMING POWER SUPPLIES	9
AN-05	
HVPS OUTPUT FALL AND DISCHARGE TIMES EXPLAINED	9
AN-06	
"JUST JUMPER THE EXTERNAL INTERLOCK"?	
WHY YOU REALLY SHOULDN'T	10
AN-07	
WHAT'S THE VOLTAGE RATING OF RG8-U COAXIAL CABLE?	11
AN-08	
HOW DO I CHANGE THE POLARITY OF THE POWER SUPPLY?	11

SECTION 3

Articles

IEEE STD 510-1983 IEEE RECOMMENDED PRACTICES FOR SAFETY IN HIGH VOLTAGE AND HIGH POWER TESTING	12
SPECIFYING HIGH VOLTAGE POWER SUPPLIES	14
HIGH VOLTAGE POWER SUPPLIES FOR ANALYTICAL INSTRUMENTATION	18
HIGH VOLTAGE POWER SUPPLIES FOR ELECTROSTATIC APPLICATIONS	22
STANDARD TEST PROCEDURES FOR HIGH VOLTAGE POWER SUPPLIES	26
COMPARATIVE TESTING OF SHIELD TERMINATIONS OF HV CABLES	37
DESIGN AND TESTING OF A HIGH-POWER PULSED LOAD	42
ACCURATE MEASUREMENT OF ON-STATE LOSSES OF POWER SEMICONDUCTORS	47
HIGHLY EFFICIENT SWITCH-MODE 100kV, 100kW POWER SUPPLY FOR ESP APPLICATIONS	52
HIGH POWER, HIGH EFFICIENCY, LOW COST CAPACITOR CHARGER CONCEPT AND DEMONSTRATION	58

SECTION 4

Glossary

	64
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FREQUENTLY ASKED QUESTIONS

ARC/SHORT CIRCUIT***Are your supplies current protected?***

Virtually all of Spellman's supplies (with the exception of a few modular proportional supplies) are "current protected." Current protection is accomplished through the use of a regulating current loop, otherwise known as current mode.

The current mode is programmed to a regulating level via the front panel pot or the remote current programming signal. A current feedback signal is generated inside the supply that drives the current meter (if there is one) and the remote current monitor signal. By comparing the current feedback signal to the current program signal, the supply can limit or regulate the output current to the desired level. Even if a continuous short circuit is placed on the output of the supply, the current mode will limit the output current to the desired preset level.

Why is the short circuit repetition rate of my load set-up important?

How frequently a power supply is short circuited is an important parameter to specify when selecting a supply for a particular application.

As a rule of thumb, most of Spellman's supplies are designed to be short circuited at a 1 Hertz maximum repetition rate. This rating is dictated by the stored energy of the output section of the supply, and the power handling capability of the internal resistive output limiter that limits the peak discharge current during short circuiting. These resistive limiters (that keep the instantaneous discharge current to a limited level) thermally dissipate the stored energy of the supply during short circuiting. If a supply is arced at a repetition rate higher than it was designed for, the resistive limiters in time, may become damaged due to overheating. Brief bursts of intense arcing usually can be handled, as long as the average short circuit rate is maintained at or below 1 Hertz.

Supplies can be modified to enhance their short circuit repetition rate by reducing their internal capacitance and/or augmenting the power handling capability of the resistive output limiting assembly. Please contact the Sales Department for additional information.

What is the difference between instantaneous short circuit current and continuous short circuit current?

The output section of a typical high voltage power supply is capacitive, which causes it to store energy. When a short circuit is placed on the output of a supply, the energy stored in the capacitance of the multiplier is discharged.

The only limit to the magnitude of short circuit current is the resistance in the series with the discharge circuit. All Spellman supplies have built-in output limiting assemblies that limit the instantaneous discharge current to a limited level. The instantaneous short circuit current is determined by the setting of the output voltage divided by the resistance that is in series with the discharge path. The amount of time this discharge event is present (and its rate of decay) is determined by the amount of capacitance and resistance present in the discharged circuit.

When a short circuit is placed upon the output of a supply, there is an instantaneous short circuit current.

Once the output capacitance has been discharged, additional output current can only come from the power generating circuitry of the power supply itself. To prevent this, the power supply will sense the rise in output current due to this short circuit condition and will automatically cross over into current mode to regulate the output current to the programmed present level.

In summary, the instantaneous short circuit current is a pulse of current that discharges the capacitance of the supply, and the continuous short circuit current is the current limit level set and controlled by the current mode of the power supply.

INTERFACING***What kind of high voltage connector do you use on your supplies?***

While most Spellman supplies typically come with one of two types of Spellman designed high voltage connector or cable arrangements, many other industry standards (Alden, Lemo, Kings, etc.) or custom cable/connectors can be provided.

Many of our lower power modular supplies are provided with a "fly wire" output cable. This output arrangement is a length of appropriately rated high voltage wire that is permanently attached to the unit. This wire may be shielded or non-shielded, depending on model. Catalog items come with fixed lengths and non-standard lengths are available via special order.

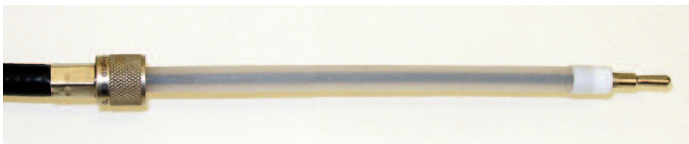
Most higher power units, both modular and rack mounted, are provided with a Spellman-designed and fabricated, detachable, high voltage cable/connector assembly, often referred to as a Delrin Connector. Typically a deep well female connector is located on the supply and a modified coaxial polyethylene cable/connector arrangement is provided. The coaxial cable's PVC jacket and braided shield

FREQUENTLY ASKED QUESTIONS

INTERFACING (continued)

is stripped back exposing the polyethylene insulation. The length of the stripped back portion depends upon the voltage rating of the supply. A banana plug is attached to the center conductor at the end of the cable and a modified UHF or MS connector shell is used to terminate where the stripped back portion of the cable ends. This allows for a simple and reliable high voltage connection to be made to the supply. Cables can be easily connected or detached as required.

Below is a photo of a typical detachable high voltage Cable. Please contact the Sales Department for additional information regarding special high voltage connector/cable and custom lengths.



Typical Detachable High Voltage Cable

Can I program your supplies with a computer?

Yes, Spellman supplies can be programmed and controlled with a computer.

Most of Spellman's newer product releases come complete with our integrated SIC Option which provides the ability to program the unit via RS-232, Ethernet or USB protocols.

Many of our standard products that do not show the SIC Option as a possible offering on the data sheet, can in some cases be modified to have the SIC Option added to them. Please consult the Sales Department for details.

Supplies that can not be provided with the SIC Option can still be computer controlled.

Virtually all of our products can be remote programmed via an externally provided ground referenced signal. In most cases 0 to 10 volts corresponds to 0 to full-scale rated voltage and 0 to full-scale rated current. Output voltage and current monitor signals are provided in a similar fashion. External inhibit signals and/or HV ON and HV OFF functioning can be controlled via a ground referenced TTL signal or opening and/or closing a set of dry contacts. More detailed information regarding interfacing is provided in the product manual.

There are several third-party vendors that sell PC interface cards that can act as an interface between the signals detailed above and a PC. These cards can be

controlled and programmed via a PC software interface usually provided by the card vendor. Please contact our Sales Department for additional information.

SAFETY***What is a safe level of high voltage?***

Safety is absolutely paramount in every aspect of Spellman's high voltage endeavors. To provide the maximum margin of safety to Spellman's employees and customers alike, we take the stand that there is no "safe" level of high voltage. Using this guideline, we treat every situation that may have any possible high voltage potential associated with it as a hazardous, life threatening condition.

We strongly recommend the use of interlocked high voltage Faraday Cages or enclosures, the interlocking of all high voltage access panels, the use of ground sticks to discharge any source of high voltage, the use of external interlock circuitry, and the prudent avoidance of any point that could have the slightest chance of being energized to a high voltage potential. The rigorous enforcement of comprehensive and consistent safety practices is the best method of ensuring user safety.

Where can I obtain information on high voltage safety practices?

One of the most comprehensive publications regarding high voltage safety practices is an excerpt from IEEE Standard 510-1983 known as "The IEEE Recommended Practices for Safety in High Voltage and High Power Testing." This information is available from Spellman in the form of a printed document included in our "Standard Test Procedures and Safety Practices for High Voltage Power Supplies" handout. Please contact our Sales Department for a copy.

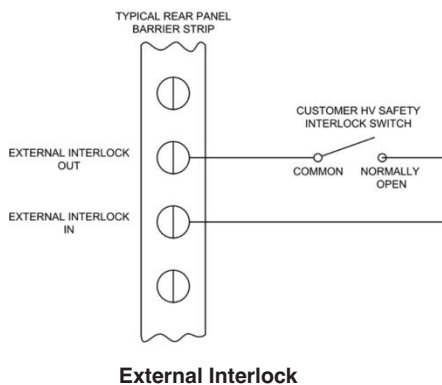
What is an "external interlock"? Why should I use it?

An external interlock is a safety circuit provided for customer use. Most interlock circuits consist of two terminals provided on the customer interface connector. A connection must be made between these two points for the power supply to be enabled into the HV ON mode. It is strongly recommended that these interlock connections be made via fail safe electro-mechanical components (switches, contactors, relays) as opposed to semiconductor transistor devices. If the power supply is already in the HV ON mode and the connection is broken between these points, the unit will revert to the HV OFF mode.

This simple circuit allows the customer to connect their own safety interlock switch to the power supply. This

SAFETY (continued)

switch could be an interlock connection on a HV access panel. In this way, if the panel was inadvertently opened, the high voltage would be turned off, greatly reducing the risk of bodily harm or physical injury. Spellman strongly recommends the use of interlock circuitry whenever possible.



TECHNOLOGY/TERMINOLOGY

What is the difference between a modular supply and a rack supply?

Modular supplies and rack supplies are the two generic categories into which Spellman's standard products typically fall. These product categories were created and used to help classify hardware. Additionally, Spellman provides a variety of custom and OEM supplies that would not adequately fit into either category.

Typically, rack mounted supplies are higher in power than their modular counterparts; but this is a generalization, not a rule. Rack mounted units usually operate off-line, requiring AC input. Rack mounted units usually provide full feature front panels, allowing quick and easy operator use. Spellman's rack mounted supplies comply with the EIA RS-310C rack-mounted standards.

Modular supplies tend to be lower power units (tens to hundreds of watts) housed in a simple sheet metal enclosure. Modular units that can operate off AC or DC inputs, can be provided. OEM manufacturers frequently specify modular supplies, knowing the elaborate local controls and monitors are usually not included, thus providing a cost savings. Customer provided signals, done via the remote interface connector, usually accomplishes operation, programming and control of these units.

When ease of use and flexibility is required, like in a laboratory environment, rack mounted supplies are usually preferred. Modular supplies tend to be specified by OEM

users, where a single specific usage needs to be addressed in the most compact and cost effective manner possible. These are guidelines, not rules.



What is the difference between voltage mode and current mode?

Voltage mode and current mode are the two regulating conditions that control the output of the supply. Most applications call for a supply to be used as a voltage source. A voltage source provides a constant output voltage as current is drawn from 0 to full rated current of the supply. In these applications, the power supply runs in voltage mode, maintaining a constant output voltage while providing the required current to the load. A voltage source is generally modeled as providing a low output impedance of the supply.

Current mode works in a similar fashion, except it limits and regulates the output current of the supply to the desired level. When the supply runs in current mode, the supply provides a constant current into a variety of load voltage conditions including a short circuit. A current source is generally modeled as providing a very high output impedance of the supply.

These two regulating modes work together to provide continuous control of the supply, but with only one mode regulating at a time. These are fast acting electronic regulating circuits, so automatic crossover between voltage mode to current mode is inherent in the design. With the programming of the voltage mode and current mode set points available to the customer, the maximum output voltage and current of the supply can be controlled under all operating conditions.

What is power control? When would it be used?

Power control, (a.k.a. power mode or power loop) is a third control mode that can be added to a variety of Spellman supplies to provide another means to control and regulate the output of the supply. Voltage mode and current mode are the primary controlling modes of most units. Taking the voltage and current monitor signal and inputting them into an analog multiplier circuit, creates a

TECHNOLOGY/TERMINOLOGY (continued)

power feedback signal (voltage x current = power). Using this feedback signal with an additional programmable reference signal in conjunction with error amplifier circuitry, a programmable power mode can be created.

Power control is typically used in two types of applications. The less common application is where the power into a load is the needed regulating parameter. A critical heating requirement may have very specific regulated thermal need. Using power mode, voltage and current limit levels can be established, and power mode will provide constant power to the load, immune from any impedance variations from the load itself.

The more popular usage of a power mode is in the area where a power source or load might be rated or capable of more current at reduced voltage levels, but limited to a particular power level. X-ray tubes frequently have this type of capability. If the maximum voltage were multiplied by this "increased current" capability, a power level above the rated power level would result. Power mode can address this problem by limiting the power to the maximum rated (or present) level.

What is floating ground?

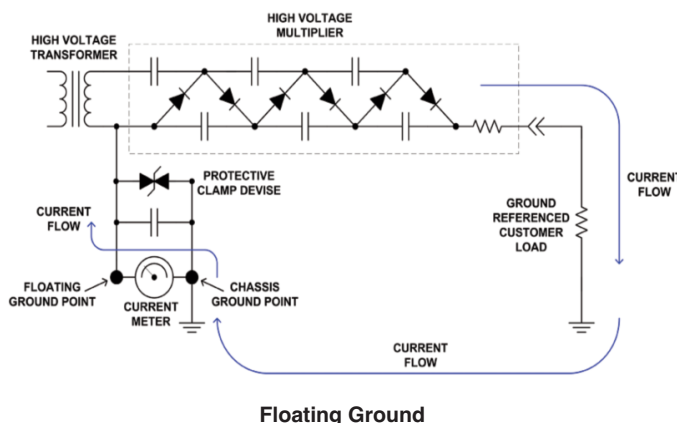
The term floating ground (FG) is used to describe an option that allows for very accurate ground referenced load current measurements to be made.

Whatever current flows out of the high voltage output of a supply, must return via the ground referenced return path. This current must return back to its original source, the high voltage output section inside the supply.

The FG option isolates all of the analog grounds inside the supply and brings them to one point: usually provided on the rear of the power supply. If a current meter is connected between this FG point and chassis ground, the actual high voltage return current can be measured in a safe ground referenced fashion.

Essentially, the analog grounds inside the supply are "floated" up a few volts to allow for this measurement. This option is only intended to allow for a ground referenced current measurement, so the actual maximum voltage the internal analog ground "floats" to, is usually limited to 10 volts maximum.

It is important to note that all control and monitoring circuitry are also floated on top of the FG terminal voltage. Users of this option must provide isolation from the FG terminal to chassis ground. Higher voltages may be available depending on the model selected. Please contact our Sales Department for more information.



What is solid encapsulation?

Solid encapsulation, also referred to as "potting," is an insulation media used in a variety of Spellman's supplies. The "output section" of a high voltage power supply can operate at extremely high voltages. The design and packaging of the high voltage output section is critical to the functionality and reliability of the product.

Solid encapsulation allows Spellman designers to miniaturize the packaging of supplies in ways that are unobtainable when utilizing air as the primary insulating media alone. Improved power densities result, providing the customer with a smaller, more compact supply.

Additionally, solid encapsulation provides the feature of sealing off a potted output section from environmental factors. Dust, contamination, humidity and vibration typically will not degrade or affect the performance of an encapsulated high voltage output section. This is especially important where a supply will operate in a harsh environment, or where a unit must operate maintenance free.

Why is oil insulation used?

Spellman has invested in and developed the use of oil insulation technology, giving its engineers and designers, when appropriate, another method of high voltage packaging technology. Oil, as an insulating media has some distinct advantages in particular situations. This capability has been utilized in several of Spellman's MONOBLOCK® designs, where a power supply and an X-ray tube assembly have been integrated into a single unit. The results of this integration include a reduction of the size and weight of a unit, in addition to providing excellent heat transfer characteristics and eliminating costly high voltage cables and connectors.

TECHNOLOGY/TERMINOLOGY (continued)

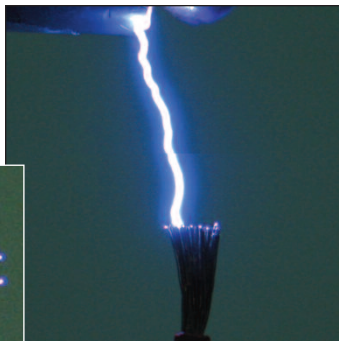
What is corona?

Corona is a luminous, audible discharge that occurs when there is an excessive localized electric field gradient upon an object that causes the ionization and possible electrical breakdown of the air adjacent to this point. Corona is characterized by a colored glow frequently visible in a darkened environment. The audible discharge, usually a subtle hissing sound, increases in intensity with increasing output voltage. Ozone, an odorous, unstable form of oxygen is frequently generated during this process. Rubber is destroyed by ozone, and nitric acid can be created if sufficient moisture is present. These items have detrimental affects on materials, inclusive of electrical insulators.

A good high voltage design takes corona generation into account and provides design countermeasures to limit the possibility of problems developing. Spellman engineers use sophisticated e-field modeling software and a Biddle Partial Discharge Detector to ensure that each high voltage design does not have excessive field gradients, preventing partial discharge and corona generation.



Corona

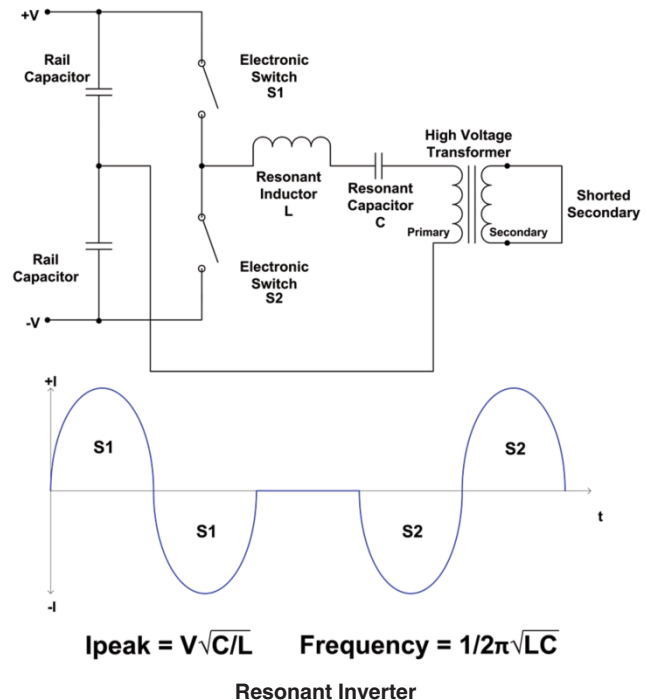


Corona and Breakdown

What is a resonant inverter?

A resonant inverter is the generic name for a type of high frequency switching topology used in many of Spellman's supplies. Resonant switching topologies are the next generation of power conversion circuits, when compared to traditional pulse width modulation (PWM) topologies.

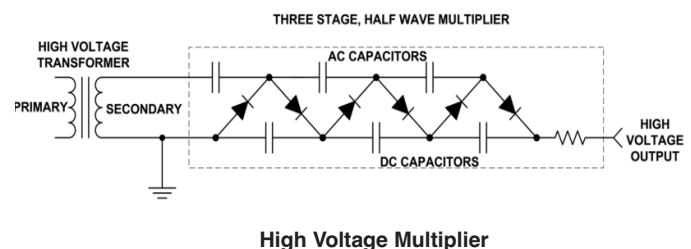
Resonant-based supplies are more efficient than their PWM counterparts. This is due to the zero current and/or zero voltage transistor switching that is inherent in a resonant supplies design. This feature also provides an additional benefit of eliminating undesirable electromagnetic radiation normally associated with switching supplies.



What is a voltage multiplier?

A voltage multiplier circuit is an arrangement of capacitors and rectifier diodes that is frequently used to generate high DC voltages. This kind of circuit uses the principle of charging capacitors in parallel, from the AC input and adding the voltages across them in series to obtain DC voltages higher than the source voltage. Individual voltage multiplier circuits (frequently called stages) can be connected in series to obtain even higher output voltages.

Spellman has pioneered the use of voltage multiplier circuits at extreme voltage and power levels. Spellman's engineers have repeatedly broken limits normally associated with this type of circuit, as they continue to lead in the development of this area of high voltage technology.



USAGE/APPLICATION

Positive polarity, negative polarity, reversible polarity; why is this important when I purchase a supply?

DC sources are polarity specific. Using earth ground as a reference point, the output of a DC supply can be "X" number of volts above ground (positive polarity) or "X" number of volts below ground (negative polarity). Another way of explaining this, is as a positive supply can source (provide) current, while a negative supply can sink (accept) current. Applications that require DC high voltage sources are polarity specific, so the polarity required must be specified at the time of order.

Can I run your supplies at maximum voltage? Maximum current? How much should I de-rate your supplies?

Spellman standard supplies can be run at maximum voltage, maximum current, and maximum power continuously with no adverse affect on performance or reliability. Each supply we sell is burned in at full rated voltage and full rated current for a minimum of 12 hours. All of our supplies are designed to meet a set of Spellman Engineering Design Guidelines that dictate all appropriate internal component deratings. Designing to these guidelines provides a supply with more than adequate margins, so there is no need to derate our supplies below our specifications.

Can I get twice the current from your supply if I run it at half voltage?

Most of our unmodified products (with the exception of several X-ray generators) obtain maximum rated power at maximum rated voltage and maximum rated current. Where more current is needed at lower voltages, we can provide a custom design for your particular application. Please contact our Sales Department to see how we can satisfy your requirement.

Why is the fall time of your supplies load dependent?

A high voltage power supply's output section is capacitive by design. This output capacitance gets charged up to the operating voltage. When the supply is placed in HV OFF or standby (or turned off entirely) this charged output capacitance needs to be discharged for the output voltage to return back to zero.

Most high voltage output sections use diodes in their output rectification or multiplication circuitry. The diodes are orientated to provide the required output polarity. A diode only allows current to flow one way. In a positive supply,

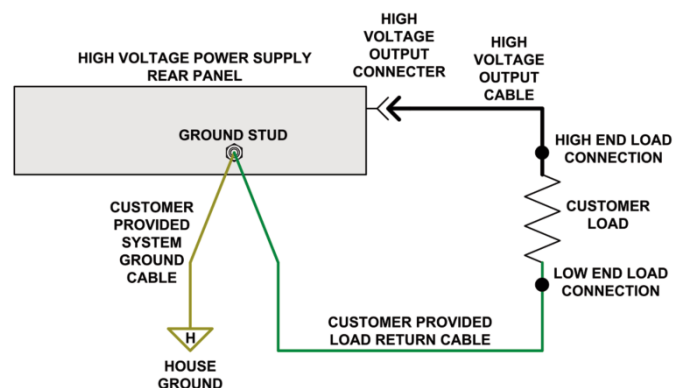
current can only flow out of the supply. Because the supply can't sink current, the charged output capacitance needs to be bled off into the customer's load or some other discharge path.

Our positive supplies actually do have a small amount of "current sink" capability provided by the resistance of the voltage feedback divider string, located inside the supply. An extremely high value of resistance is necessary (typically tens or hundreds of meg-ohms, or even gig-ohms) so the output capacitance will bleed off to zero volts, in seconds or tens of seconds in a "no load" condition. For this reason, the fall time of our supplies are load dependent.

How should I ground your supply?

Grounding is critical to proper power supply operation. The ground connection establishes a known reference potential that becomes a baseline for all other measurements. It is important that grounds in a system are low impedance, and are connected in such a way that if currents flow through ground conductors they do not create voltage level changes from one part of the system to another.

The best way to minimize the possibility of creating voltage differences in your system grounding is to use ground planes via chassis and frame connections. Since the source of the high voltage current is the power supply, it is recommended that it be the tie point for system grounds to other external devices.



Power Supply Grounding

The rear panel of the power supply should be connected to this system ground in the most direct, stout manner possible, using the heaviest gauge wire available, connected in a secure and durable manner. This ties the chassis of the supply to a known reference potential. It is important to understand most damage to HV power supplies occur during load arcing events. Arcing produces very high transient currents that can damage power sup-

USAGE/APPLICATION (continued)

ply control circuitry (and other system circuitry) if grounding is not done properly. The product manual provides more detailed information regarding grounding requirements. If you have any additional questions, please contact the Sales Department.

Can I float your supplies?

Spellman's standard products are for the most part, designed and intended for use as ground referenced power supplies. That is, only one high voltage output connection is provided, while the current return path is made via the customer-provided ground referenced load return wiring. This load return must be connected to a reliable earth ground connection for proper operation and transient protection.

Many applications do exist, like ion beam implantation, which require supplies to operate at reference voltages other than earth ground. A supply of this nature is said to "float" at some other reference potential. If your application requires a floating power supply, please contact our Sales Department to review your requirement.

AN-01***What do you mean; the output is "ground referenced"?***

Most of Spellman's standard catalog products are termed to be "ground referenced power supplies". A ground referenced power supply typically only has only one (1) rated high voltage output connector. Internally the high voltage multiplier return is referenced to the grounded chassis of the unit. This chassis is referenced to "house ground" in the customer's system via the safety ground wire in the power cable and a separate customer provided system ground connection. With the output of the supply ground referenced it is easy to sample the output voltage and current to obtain the feedback signals needed to regulate the supply. A high impedance, ground referenced, high voltage feedback divider monitors the output voltage, while a ground referenced current feedback resistor placed in series with the multiplier return monitors the output current.

With the customer's load being referenced to ground the circuit is complete. All measurements made with regards to the power supply utilize earth ground as the reference potential. Ground referencing a power supply simplifies its design, and fabrication. All programming and monitoring signals are also ground referenced, simplifying operation of the power supply.

Ground referenced power supplies can not in their native form be "stacked one on top of another" to obtain higher output voltages. All output circuitry is referenced to ground, preventing it from being connected to any other voltage source or reference potential.

AN-02***"Ground is ground", right? Well, not always. What you need to know.***

Ground is one of those "ideal" things like the "ideal switch" that's spoken about in engineering school. An ideal switch has all the good characteristics (no losses, zero switch time, etc) and no bad ones. The truth is, ground is only as good as you make it, and only keeps its integrity if you do the right thing.

It's much easier to start from scratch and create a good ground system than to try to fix a bad one. Grounding problems can be difficult to isolate, analyze and solve. Here are a few tips on creating a good ground system that will benefit both your high voltage power supply and the rest of your system.

A ground system starts with whatever you use as your ground reference point. There are several that can be used: cold water pipe, electrical service conduit pipe, electrical service ground wire, a building's steel girder framework, or the old fashioned ground rod. Whichever you use; connect this point to the ground stud on the HVPS with a short, heavy gauge wire and appropriate lug. Earth is the universal reference point and by tying the HVPS to it in this manner you will create a good reference point.

The next important ground connection that's needed is the load return. Whatever current comes out of the HVPS (be it continuous rated current or transient arc current) must have a return path back to the power supply. This path should be an actual physical wire; again of a short, heavy type. With this connection the large transient arc currents will travel in a known path, without influencing other ground referenced equipment.

Just a point of clarification: the "3rd green ground wire" in the AC power line cord is NOT an adequate system ground. This wire is a safety ground not intended to be used as part of a grounding system. A washing machine typically has a metal chassis. If an AC power wire popped off inside and touched against the chassis you wouldn't want to open the lid and get shocked. Here, the "3rd wire" grounds the chassis, preventing a shock by bypassing the current to earth. That is its function; to be only a redundant safety ground. Don't rely on this connection as part of your system ground scheme.

Connect all additional system ground references to the main grounding point of the high voltage power supply. Be it a "star" ground system or a ground frame/plane system, attached the ground connection to the power supply main grounding point. Following these recommendations will help create a proper functioning grounding system.

AN-03***You wouldn't use a pickaxe for dental surgery: When over specifying a power supply can be a bad thing.***

Selecting the right power supply for the task at hand will reward you in several ways like: reduced size, weight, cost and superior performance. Over specifying and purchasing "more supply than you need" can actually result in degraded system performance in some circumstances.

All Spellman power supplies are designed, built and tested at their full rated output voltage and current. We have applied the appropriate component deratings for reliable long term operation at full rated voltage and current. No additional deratings of our power supplies are required.

AN-03 (continued)

If you need 30kV, buy a 30kV unit and run it at 30kV; it's what it was designed to do. The same goes for current and power. You will get the most bang for the buck buying a supply that closely fits your requirements. If you can afford a larger, heavier and more expensive supply there is nothing wrong with having a bit more capacity, but, over specifying is NOT required to get reliable operation. Minor over specifying can result in additional weight, size and cost. Gross over specifying can actually degrade system performance.

You wouldn't use a 4 inch wide exterior house paint brush to touch up delicate interior wooden trim molding. A large brush is great for quickly applying a lot of paint to a big area, but a smaller brush allows better application and control when painting smaller items. Size the tool for the intended job to get the best results.

Power supplies are similar. A 30kV supply can operate down at 250 volts, but when running at less than 1% of its rated output, it can be somewhat hard to control with great resolution. A 500 volt or even 1kV rated maximum output supply would more adequately address this requirement.

None of our supplies have any "minimum load requirements". But keep in mind if excellent low voltage or low power operation is required select a supply with maximum ratings that are close to your needs. It's easier to obtain precision operation when the power supply is properly scaled and selected for its intended usage. If not, issues like miniscule program and feedback signals, signal to noise ratios, feedback divider currents can make operating a supply at very small percentages of its maximum rated output very difficult.

AN-04
How low can you go?
Why signal to noise ratios are important in programming high voltage power supplies.

Virtually all Spellman power supplies are programmable; usually a 0 to 10 volt ground referenced analog programming signal is proportional to 0 to 100% of full scale rate voltage and/or current. Modular supplies typically only accept a remotely provided signal, while rack units also have front panel mounted multi-turn potentiometers to provide local programming capability.

Let's look at two example units, where 0 to 10 volts of voltage programming equates to 0 to 100% of output voltage. The first unit is an SL100P300 (100kV maximum) and the second unit is an SL1P300 (1kV maximum).

If a rather low output voltage of 100 volts was desired, let's look at the level of programming voltage each unit requires.

SL100P300	SL1P300
$(100/100,000) (10) = 10\text{mV}$	$(100/1000) (10) = 1\text{ volt}$

The SL100P300 needs a programming signal of 10mV, while the SL1P300 needs a programming signal of 1 volt to achieve the same 100 volt output.

Noise is present in most electrical systems; it's the low level background signal that is due to switching regulators, clock circuits and the like. Ideally zero noise would be desired, but some amount is present and must be dealt with. In a power supply like the SL Series 25mV of background noise on the analog control lines is not uncommon. Ideally we would like to have the programming signal as large as possible, so the noise signal has the least amount of influence. Let's see how that noise affects the signals of our two example power supplies.

SL100P300	SL1P300
Signal = 10mV	Signal = 1000mV (1 volt)
Noise = 25mV	Noise = 25mV
s/n ratio: signal is smaller than noise	s/n ratio: signal is 40X larger than noise

It's easy to see that getting a stable, repeatable 100 volt output from the SL100P300 will be quite difficult, while this is easy to do with the SL1P300.

When low output voltages are needed think about the programming signals required and how they compare to the system noise levels. Doing so will provide a stable, repeatable output where noise has minimal effect.

AN-05
"No, you touch it". HVPS output fall and discharge times explained.

When working with high voltage power supplies knowing about output fall and discharge times can be helpful. Consider this information as only providing additional details on power supply functionality. This application note by itself is not adequate "safety training" for the proper setup and use of a HVPS. Please refer to the complete safety information provided with our products.

AN-05 (continued)

Typically, high voltage is created by controlling an inverter that feeds a step up transformer which is connected to a voltage multiplier circuit. This multiplier circuit (an arrangement of capacitors and diodes) uses the principle of charging and discharging capacitors on alternate half cycles of the AC voltage, where the output is the sum of these capacitor voltages in series. By definition, the voltage multiplier circuit is capacitive in nature and has the ability to store and hold charge.

For the sake of efficiency, any internal current paths to ground are minimized. Typically the only resistive path connecting the output of the supply to ground is the high impedance voltage feedback divider string. This feedback divider generates the low level, ground referenced, voltage feedback signal used to control and regulate the supply.

Due to the orientation of the diodes in the multiplier assembly, a positive polarity supply can only source current; it has no ability to sink current. So the feedback divider string becomes the only discharge path for the output during a "no-load" condition. Let's look at a typical unit's value of multiplier capacitance and feedback divider resistance to see what kind of no load RC discharge time constants we're talking about.

SL60P3000

60kV, 0- 5mA, 300 watts

C multiplier = 2285pF R feedback = 1400MΩ

RC = (2285pF) (1400MΩ) = 3.199 seconds

5 RC time constants required to approach zero (≈1.2%)

(5) (3.199 seconds) = 15.995 seconds

The above example illustrates how under a no load condition it can take considerable time for the output to discharge. If an external load is left connected to the supply's output, the discharge time constant can be shortened considerably. For this reason HVPS fall times are termed to be "load dependent". Keep this in mind when working with your next HVPS.

AN-06

***"Just jumper the external interlock"?
Why you really shouldn't.***

Many Spellman high voltage power supplies come with an external interlock feature. Typically the external interlock is provided by means of two signal connections on the rear panel terminal block or interface connector. This feature provides the user the ability to shut off and prevent the generation of high voltage in a fail safe manner. This external interlock circuitry can easily be incorporated into the user's setup to provide an additional level of operator safety.

In most cases the current of the relay coil that is used to latch the power supply into the HV ON mode is routed out to, and back from, the rear panel external interlock points. This is usually a low voltage relay coil; 12Vdc or 24Vdc with current in the range of tens of milliamps. The two external interlock points must be connected together with a low impedance connection to allow the power supply to be placed into, (and to continue to operate in) the HV ON mode.

Opening this connection will prevent the supply from being placed in the HV ON mode. Additionally, if the unit was actively running in the HV ON mode, open this connection would cause the power supply to revert to the HV OFF mode. The external interlock is the best method of controlling the power supply output with regards to safety, other than disconnecting the power supply from its input power source.

Typically our power supplies are shipped with the two external interlock connections jumpered together to allow quick and easy operation of the supply. Leaving the unit configured in this manner does indeed work, but it bypasses the external interlock function.

Spellman recommends that any exposed high voltage potential be isolated from contact through the use of appropriate physical barriers. High voltage cages or enclosures should be used to protect operators from inadvertent contact with potentially lethal voltages. Doors and/or access panels of these cages or enclosures should have a normally open interlock switch installed on them such that the switch is in the closed state only when the door or panel is in the secured position. Opening the door or panel will revert the power supply to the HV OFF mode, and prevent the supply from being placed in the HV ON mode until the door or panel is properly secured.

AN-07

What's the voltage rating of RG8-U coaxial cable?

Output cable and connectors are not trivial items for power supplies where output voltages can be 100,000 volts or higher. The cables and connectors used must function together as a system to safely and reliably access and provide the power supplies output for customer usage.

In many high voltage power supply applications, a shielded polyethylene coaxial cable is used. Polyethylene cables provide excellent high voltage dielectric isolation characteristics in a small but robust form factor. The shield conductor provided in a coaxial cable functions as a "Faraday Shield" for the center conductor of the cable that is referenced to the high voltage potential. If any breakdown in the main insulator occurs, the high voltage current will be bypassed to the grounded shield conductor that surrounds the main insulator. This inherent safety feature is one benefit of using a coaxial high voltage output cable.

RG8-U has long been used as a high voltage output cable in the high voltage industry. There is a variation of RG8-U that utilizes a solid polyethylene core. Specifications for this cable do not specify actual "high voltage" ratings, since this cable was not designed and fabricated with high voltage usage in mind. So the reality is, there are no high voltage ratings for RG8-U. Over the years others in the HV industry have used this cable at 20kV, 30kV and even higher voltages. Spellman does use RG8-U cable, but limits its usage to applications where the maximum voltage that will be applied to the cable is 8kV or less.

For voltages above 8kV where a coaxial polyethylene cable is desired, Spellman uses cables specifically designed and manufactured for high voltage usage.

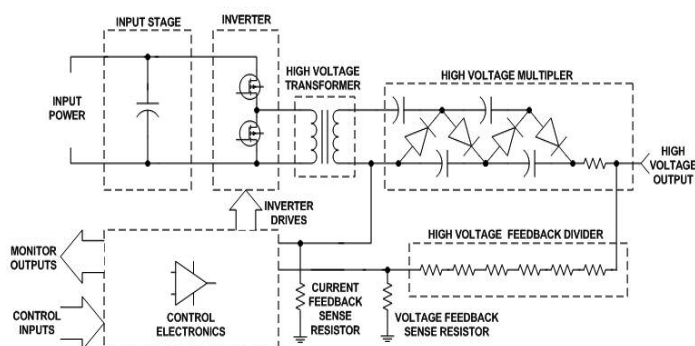
These cables are of the same general design; as described above but the insulating core material diameter has been increased appropriately to obtain the desired dielectric insulating capability required. Frequently higher voltage versions of these cables utilize a thin semiconductor "corona shield". This corona shield is located between the metallic center conductor and the main polyethylene insulating core. This corona shield helps equalize the geometric voltage gradients of the conductor and by doing so reduces the generation of corona.

A high voltage cable and connector system can only be as good as the materials used to make it. Using cables that are designed, specified and tested specifically for high voltage usage assures that these materials are used within their design guidelines.

AN-08

How do I change the polarity of the power supply?

How do I change the polarity of the power supply? Most high voltage power supplies use a circuit called a voltage multiplier to create the desired high voltage output. This basic multiplier circuit is shown below in the simplified power supply block diagram:



Simplified Schematic Diagram of a High Voltage Power Supply

The multiplier circuit is comprised of an arrangement of capacitors and diodes. The orientation of the diodes will determine the output polarity of the unit. In the example above, the diodes shown would create a positive output polarity with respect to ground. If each diode was reversed in orientation, the multiplier would generate a negative output voltage with respect to ground.

The example above only shows a two stage, half-wave multiplier; using a total of four diodes. Full-wave multiplier stages are more efficient and use additional capacitors and twice as many diodes. To generate the high voltages typical of a Spellman supply, many multiplier stages are connected in series. If a twelve stage, full wave multiplier was made, a total of 48 diodes would be required.

Typically the capacitors and diodes used to fabricate a multiplier assembly are soldered directly to a single or sometimes several printed circuit boards. Frequently this assembly is encapsulated for high voltage isolation purposes.

To simplify the process of reversing the polarity (like in the instance of the SL Series) a second "opposite polarity" multiplier is provided above 8kV when reversibility is required. Exchanging the multiplier is a simple task needing only a screwdriver and few minutes of time. Modular style units due to their simplified design, are typically not capable of having their polarity changed in the field.

ARTICLES

IEEE Std 510-1983 IEEE Recommended Practices for Safety

IEEE Std 510-1983 IEEE Recommended Practices for Safety in High Voltage and High Power Testing

by The Institute of Electrical and Electronics Engineers

SCOPE

Excerpts from IEEE Standard 510-1983 have been listed in this section in order to caution all personnel dealing with high voltage applications and measurements and to provide recommended safety practices with regard to electrical hazards.

Considerations of safety in electrical testing apply not only to personnel but to the test equipment and apparatus or system under test. These recommended practices deal generally with safety in connection with testing in laboratories, in the field, and of systems incorporating high voltage power supplies, etc. For the purposes of these recommended practices, a voltage of approximately 1,000 volts has been assumed as a practical minimum for these types of tests. Individual judgement is necessary to decide if the requirements of these recommended practices are applicable in cases where lower voltages or special risks are involved.

- All ungrounded terminals of the test equipment or apparatus under test should be considered as energized.
- Common ground connections should be solidly connected to both the test set and the test specimen. As a minimum, the current capacity of the ground leads should exceed that necessary to carry the maximum possible ground current. The effect of ground potential rise due to the resistance and reactance of the earth connection should be considered.
- Precautions should be taken to prevent accidental contact of live terminals by personnel, either by shielding the live terminals or by providing barriers around the area. The circuit should include instrumentation for indicating the test voltages.
- Appropriate switching and, where appropriate, an observer should be provided for the immediate de-energization of test circuits for safety purposes. In the case of dc tests, provisions for discharging and grounding charged terminals and supporting insulation should also be included.
- High Voltage and high-power tests should be performed and supervised by qualified personnel.

TEST AREA SAFETY PRACTICES

- Appropriate warning signs, for example, DANGER – HIGH VOLTAGE, should be posted on or near the entrance gates.
- Insofar as practical, automatic grounding devices should be provided to apply a visible ground on the high-voltage circuits after they are de-energized. In some high-voltage circuits, particularly those in which elements are hanged from one setup to the next, this may not be feasible. In these cases, the operator should attach a ground to the high-voltage terminal using a suitably insulated handle. In the case of several capacitors connected in series, it is not always sufficient to ground only the high-voltage terminal. The exposed intermediate terminals should also be grounded. This applies in particular to impulse generators where the capacitors should be short-circuited and grounded before and while working on the generator.
- Safe grounding of instrumentation should take precedence over proper signal grounding unless other precautions have been taken to ensure personnel safety.

CONTROL & MEASUREMENT CIRCUITS

- Leads should not be run from a test area unless they are contained in a grounded metallic sheath and terminated in a grounded metallic enclosure, or unless other precautions have been taken to ensure personnel safety. Control wiring, meter connections, and cables running to oscilloscopes fall into this category. Meters and other instruments with accessible terminals should normally be placed in a metal compartment with a viewing window.
- Temporary Circuits
- Temporary measuring circuits should be located completely within the test area and viewed through the fence. Alternatively, the meters may be located outside the fence, provided the meters and leads, external to the area, are enclosed in grounded metallic enclosures.
- Temporary control circuits should be treated the same as measuring circuits and housed in a grounded box with all controls accessible to the operator at ground potential.

SAFETY RULES

- A set of safety rules should be established and enforced for the laboratory or testing facilities. A copy of these should be given to, and discussed with, each person assigned to work in a test area. A procedure for periodic review of these rules with the operators should be established and carried out.

ARTICLES

IEEE Std 510-1983 IEEE Recommended Practices for Safety

SAFETY INSPECTION

- A procedure for periodic inspection of the test areas should be established and carried out. The recommendations from these inspections should be followed by corrective actions for unsafe equipment or for practices that are not in keeping with the required regulations.

NOTE: *A safety committee composed of several operators appointed on a rotating basis has proven to be effective, not only from the inspection standpoint but also in making all personnel aware of safety.*

GROUNDING & SHORTING

- The routing and connections of temporary wiring should be such that they are secure against accidental interruptions that may create hazard to personnel or equipments.
- Devices which rely on a solid or solid/liquid dielectric for insulation should preferably be grounded and short-circuited when not in use
- Good safety practice requires that capacitive objects be short-circuited in the following situations:
- Any capacitive object which is not in use but may be in the influence of a dc electric field should have its exposed high-voltage terminal grounded. Failure to observe this precaution may result in a voltage included in the capacitive object by the field.
- Capacitive objects having a solid dielectric should be short-circuited after dc proof testing. Failure to observe this precaution may result in a buildup of voltage on the object due to dielectric absorption has dissipated or until the object has been reconnected to a circuit.

NOTE: *It is good practice for all capacitive devices to remain short-circuited when not in use.*

- Any open circuited capacitive device should be short-circuited and grounded before being contacted by personnel.

SPACING

- All objects at ground potential must be placed away from all exposed high voltage points at a minimum distance of 1 inch (25.4 mm) for every 7,500 Volts, e.g. 50 kV requires a spacing of at least 6.7 inches (171 mm).
- Allow a creepage distance of 1 inch (25.4 mm) for every 7,500 Volts for insulators placed in contact with high voltage points.

HIGH-POWER TESTING

- High-power testing involves a special type of high-voltage measurement in that the level of current is very high. Careful consideration should be given to safety precautions for high-power testing due to this fact. The explosive nature of the test specimen also brings about special concern relating to safety in the laboratory.
- Protective eye and face equipment should be worn by all personnel conducting or observing a high-power test where there is a reasonable probability that eye or face injury can be prevented by such equipment.

NOTE: *Typical eye and face hazards present in high-power test areas included intense light (including ultraviolet), sparks, and molten metal.*

- Safety glasses containing absorptive lenses should be worn by all personnel observing a high-power test even when electric arcing is not expected. Lenses should be impact-resistant and have shade numbers consistent with the ambient illumination level of the work area but yet capable of providing protection against hazardous radiation due to any inadvertent electric arcing.

GENERAL

- All high-voltage generating equipment should have a single obvious control to switch the equipment off under emergency conditions.
- All high-voltage generating equipment should have an indicator which signals that the high-voltage output is enabled.
- All high-voltage generating equipment should have provisions for external connections (interlock) which, when open, cause the high-voltage source to be switched off. These connections may be used for external safety interlocks in barriers or for a foot or hand operated safety switch.
- The design of any piece of high-voltage test equipment should include a failure analysis to determine if the failure of any part of the circuit or the specimen to which it is connected will create a hazardous situation for the operator. The major failure shall be construed to include the probability of failure of items that would be overstressed as the result of the major failure. The analysis may be limited to the effect of one major failure at a time, provided that the major failure is obvious to the operator.

ARTICLES

Specifying High Voltage Power Supplies

Specifying High Voltage Power Supplies

by Derek Chambers and Cliff Scapellati

INTRODUCTION

In specifying a regulated high voltage power supply for a particular application, it is important to bear in mind that recent advances in power supply technology have made the latest designs smaller, lighter, more efficient than was possible just a few years ago. New designs generally operate at high frequencies in the range of 20kHz to 100kHz, and industry-wide, have virtually replaced all units operating at line frequency, even at high power levels.

All high voltage power supplies must be operated by personnel familiar with the dangers of high voltage. High voltage sources can be lethal! A general guideline for Safety Practices is found in IEEE Standard 510-1983 "Recommended Practices for Safety in high voltage and high power testing."

The two primary factors which have led to these developments are:

- The availability of key power components which have low losses while operating at high frequency
- The development of advanced resonant power conversion techniques

Key Power Components include:

- Faster switching devices (e.g. transistors, power MOSFETS, IGBTs, SCRs)
- Low loss ferrite and powdered iron core materials for choke and transformer cores
- Capacitors with low dissipation factors
- Ultra fast rectifiers which have a low forward voltage drop

Advanced Conversion Techniques include:

- Zero current switching series and parallel resonant inverters (discontinuous mode);
- Zero voltage switching LCC resonant inverters (continuous mode)
- Soft switching and phase controlled resonant inverters
- Quasi-resonant flyback and push-pull inverters

Compared with line frequency operation, high frequencies offer the following advantages in regulated high voltage power supplies:

- Smaller size and weight
- Faster response time
- Lower stored energy
- Higher efficiency



High-voltage supplies such as this multiple-output model use more efficient and higher-performance components and power conversion techniques to reduce weight and improve performance.

TECHNOLOGY

The heart of any high frequency power supply is the oscillator (or inverter) used to drive the output transformer. The specific designs used in the high voltage power supply industry are too numerous to cover in this article since each manufacturer has developed his own proprietary power switching circuits. However, there is one factor, unique to high voltage power supplies, that must be considered in the choice of the oscillator or inverter topology. Specifically, the capacitance which exists across the secondary winding of the step-up transformer must be isolated from being reflected directly across the power switching semiconductor. This isolation can be achieved in a number of ways, including:

- Using a flyback circuit
- Using an inductor or a series resonant circuit between the switching devices and the transformer
- Including sufficient leakage inductance between the primary and secondary windings of the transformer
- Operating as a self resonant oscillator

The choice of oscillator topology is also influenced by the power level of the supply. For instance, a low power unit for a photomultiplier application could use a flyback or self resonant oscillator, while higher power models (e.g. over a kilowatt) would be more likely to use a driven inverter feeding the output transformer through an inductor or a series resonant circuit. The transformer may also be designed to form part of the resonant inverter power circuit.

ARTICLES

Specifying High Voltage Power Supplies

Properly designed resonant converter designs offer the following desirable characteristics:

- Zero current switching, which improves efficiency and minimize the switching losses in the high power switching devices
- Sinusoidal current waveforms in the power inverter circuit, which greatly reduce RFI interference normally associated with pulse width modulation techniques
- Simple paralleling of the supplies to obtain higher output power
- Inherent current limiting and short circuit protection of series resonant inverters

SPECIFICATION CONSIDERATIONS

Probably the most common mistake engineers make in defining a high voltage power supply is to over specify the requirements for output power, ripple, temperature stability, and size. Such over specification can lead to unnecessarily high cost, and can also lower reliability due to increased complexity and greater power density. If a particular parameter in the catalog specification is inadequate for the application, the factory should be consulted.

UNDERSTANDING SPECIFICATION PARAMETERS

The specifications provided by the power supply manufacturer generally include information on the input and output voltages, the output regulation, ripple, and output stability. Often, more detailed information would be useful to the user. In the following sections, power supply parameters are discussed in greater detail than is normally possible on a standard data sheet, and includes definitions and descriptions of requirements encountered by users of high voltage power supplies.

The specification parameters are covered in the following order:

- Input Voltage
- Output Voltage
- Output Current
- Ripple
- Stability
- Stored Energy
- Pulsed Operation
- Line Regulation
- Load Regulation
- Dynamic Regulation
- Efficiency



Higher-power high-voltage supplies, like Spellman's series SL which are rated up to 1,200W, operate from ac line power.

INPUT VOLTAGE

The input power source specified for a particular model is determined by a number of factors including the output power capability of the supply and the form of power available in the application. In general, low power high voltage supplies having outputs between 1W and 60W use a dc input voltage of 24V or 28V, while higher power units operate from the ac power line.

DC Input

In many OEM applications, the high voltage supply is just one part of an electronic system in which dc power sources are already available (e.g. 24Vdc, 390Vdc). These existing dc supplies can also be used as the input power source for a high voltage supply. This arrangement is convenient and economical for modular high voltage supplies operating at low power levels.

AC Input

Most high power modules over 100W, and rack mounted models are designed for operation from an ac line source. These power supplies are designed to accept the characteristics of the power line normally available at the location of the user, and these can vary significantly in different parts of the world.

In the United States and Canada, the standard single phase voltage is 115/230Vac at 60Hz, while in Continental Europe and in many other parts of the world, the standard voltage is 220Vac at 50Hz. In the UK, the standard is 240Vac at 50 Hz, while in Japan the voltage is normally 100V at 50 or 60Hz. Most power supplies include transformer taps to cover this range, while some new designs cover the range 90Vac to 130Vac and 180Vac to 260Vac without taps. All countries in the European Economic Community will eventually standardize at 230V at 50Hz.

Power Factor correction and universal input at power levels below 3kW can be specified for most off-the-shelf high voltage power supplies. Higher power units require custom engineering.

ARTICLES

Specifying High Voltage Power Supplies

OUTPUT VOLTAGE

High voltage power supplies are generally designed for continuous operation at the maximum output voltage specified in the data sheet. Laboratory bench models and high power rack units are normally adjustable over the complete voltage range from zero to the maximum specified output voltage. In these models, output voltage is indicated on either digital or analog meters, as specified. Modular supplies, on the other hand, may have either a preset output voltage, or a narrow adjustment range, and include monitor terminals instead of meters for measuring the voltage. It is not generally cost effective to specify a power supply with an output voltage greater than 20% over the maximum voltage actually needed in a particular application.

OUTPUT CURRENT

Power supplies are normally designed for continuous operation at the full current specified in the data sheet. Current limiting is normally built into the design to prevent overload current from increasing beyond about 110% of the rated maximum value of output current. Overload trip out can usually be specified to disable the power supply when the normal output current is exceeded. Current regulation is available on most high power racks and modules. This allows the output current to be controlled by a front panel potentiometer or from a remote source, and provides automatic crossover to voltage regulation when the load current is lower than the programmed value.

RIPPLE

Ripple may be defined as those portions of the output voltage that are harmonically related to both the input line voltage and the internally generated oscillator frequency. In high frequency switching designs it is the combined result of two frequencies, namely, the line frequency-related components and the switching frequency related components. Total ripple is specified either as the rms, or the peak-to-peak value of the combined line frequency and oscillator frequency components, and is normally expressed as a percentage of the maximum output voltage.

The amount of ripple that can be tolerated in different applications varies from extremely low values (e.g. less than 0.001% peak to peak in photomultiplier, nuclear instrumentation and TWT applications) to several percent when the output can be integrated over time, such as in precipitators and E-beam welding.

The high frequency ripple may generally be reduced by adding capacitance across the output. On the other hand, when there is a fast response time requirement, the value of output capacitance may have to be reduced. In critical cases, the trade off between slew rate and ripple should be worked out between the customer and the manufacturer of the power supply.

Line frequency ripple:

When operating from an ac input source, line frequency ripple can represent a significant part of the total peak to peak ripple. Typically, the power supply is designed to have equal amounts of high frequency and line frequency ripple when operating at full output power. It should be noted that, in most designs, the magnitude of the line frequency ripple is attenuated and controlled by feedback in the regulation circuits, which normally have bandwidths to include the line ripple frequency.

Switching frequency ripple:

In regulated supplies operating from a dc input, line frequency ripple does not exist, and the ripple frequency is simply related to the switching or oscillator frequency of the supply. To reduce switching frequency output ripple, additional filtering components, or sometimes electronic ripple canceling circuits, may be used. When filtering components, such as shunt capacitors or series resistors or inductors, are added to reduce the ripple, they introduce a delay in the control loop circuits which adversely affects the response time of the supply to changes in input or output conditions. The values of the components which control the phase of the signal in the feedback loop are then changed at the factory to maintain stable operation.

If an application requires particularly small values of either high frequency or line frequency ripple, it is usually possible to provide a lower ripple at one of these frequencies at the expense of increasing the ripple at the other. In these special cases, the requirements should be discussed with the factory before an order is placed.

STABILITY

The following factors affect the output stability of a regulated high voltage power supply:

- Drift in the reference voltage;
- Offset voltage changes in the control amplifiers;
- Drift in the voltage ratio of the feedback divider;
- Drift in the value of the current sense resistor.

All these variations are a function of temperature. Stability in a properly chosen reference device is generally less than 5ppm, and offset errors can be virtually eliminated by careful choice of the control amplifier. This leaves the volt-

ARTICLES

Specifying High Voltage Power Supplies

age divider and the current sense resistor as the critical items affecting stability in the output voltage and current.

Since these components are sensitive to temperature variations, they are selected to operate at a fraction of their power capability, and are located away from hot components. However, as the power supply warms up and the ambient temperature around the components increases, there are small changes in the ratio of the voltage divider and the value of the current sense resistor which could affect stability.

The values for stability are usually given after a specified warm-up period (typically 1/2 hour). Good stability is achievable by using a divider with a low value of temperature coefficient, although this becomes more costly.

STORED ENERGY

The stored energy at the output of a high voltage power supply can be dangerous to operating personnel, particularly at the higher voltages since its value is a function of the square of the voltage and the value of the capacitance across the output. Certain types of loads, such as X-ray tubes, are also easily damaged by excessive stored energy in the high voltage power supply when an arc occurs. With power supplies operating at high frequency rather than at line frequency, much smaller values of smoothing capacitance can be used, and the dangers of electrocution are thereby reduced. However, it should be noted that low ripple power supplies which include additional filtering capacitance across the output have correspondingly higher amounts of stored energy. Compared with a power supply operating at line frequency, a switching supply operating at 60kHz could have a fraction of the stored energy of an equivalent line frequency supply, since the value of the output capacitance could be reduced by 1000.

PULSED OPERATION

While some power supplies are designed for dc operation, others can be used in pulsed power applications. In most cases, an energy storage capacitor located inside or external to the supply provides the peak pulse current, and the power supply replaces the charge between pulses. The supply operates in the current mode during the pulse and recharging parts of the cycle, and returns to the voltage mode before the next load current pulse.

Pulsed loads generally fall into one of three categories:

- Very narrow pulses (1usec to 10usec), with a duty ratio of 0.01% to 1%
- Longer pulses (100usec to 1msec), with a duty ratio between 0.05% and 0.2%
- Very long pulses (50msec to 5sec), with a duty ratio between 0.1% and 0.5%

The first category includes pulsed radar applications in which narrow pulses, having durations in the microsecond range, are generated at typical repetition rates between 500Hz and 5kHz.



Compact high power module delivers to 350 watts CW or 600 watts pulse for projection television and CRT testing. 1kV to 70kV with voltage and current programming and monitoring.

The second category covers a broader range of applications such as pulsed electromagnet supplies or cable testing where most of the pulse load current is still provided by a capacitor connected across the output. Some modifications to the output and control circuits are usually needed for reliable operation in these applications, and the details of the load characteristics should be discussed with the factory to ensure reliable operation in the customer's system.

The third category requires a power supply specifically designed to provide more current than its average rated value for relatively long periods. Typical applications are medical X-ray systems, lasers and high voltage CRT displays. It is essential that the actual load conditions are completely specified by the user before placing an order.

LINE REGULATION

Line regulation is expressed as a percentage change in output voltage for a specified change in line voltage, usually over a $\pm 10\%$ line voltage swing. Measurement is made at maximum output voltage and full load current unless otherwise stated. Line regulation of most high voltage power supplies is better than 0.005%.

LOAD REGULATION

Load Regulation is specified at full output voltage and nominal line voltage and is expressed as a percentage change in output voltage for a particular load current change, usually no load to full load. Typical load regulation of most high voltage supplies is better than 0.01%.

ARTICLES

High Voltage Power Supplies for Analytical Instrumentation

High Voltage Power Supplies for Analytical Instrumentation

by Cliff Scapellati

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

A.) 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 <24V to 480V are common. DC sources ranging from 5V to 300V 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.

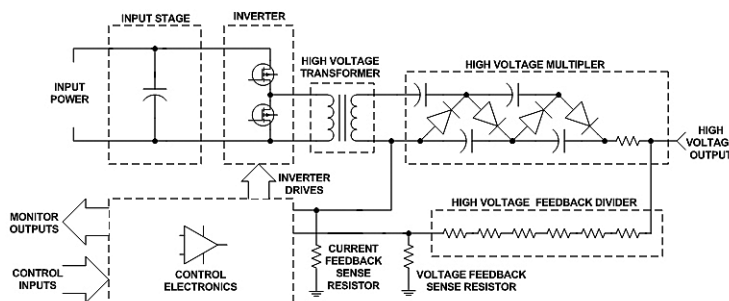


Fig. 1 Basic High Voltage Power Supply

B.) 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.

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

High Voltage Power Supplies for Analytical Instrumentation

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.

C.) 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.

D.) 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 in variably 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

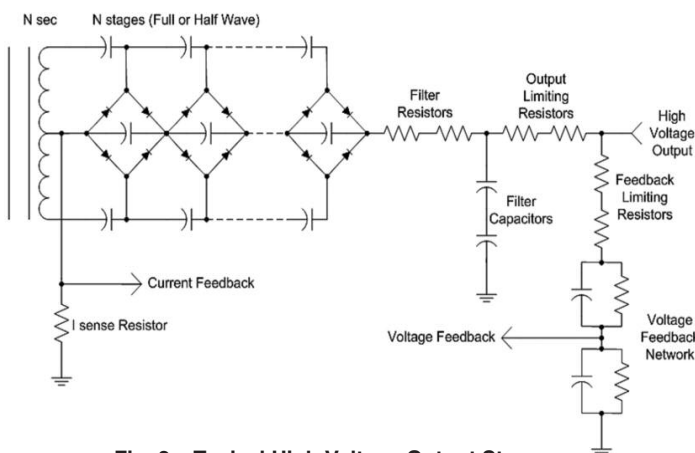


Fig. 2 Typical High Voltage Output Stage

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.

E.) 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.

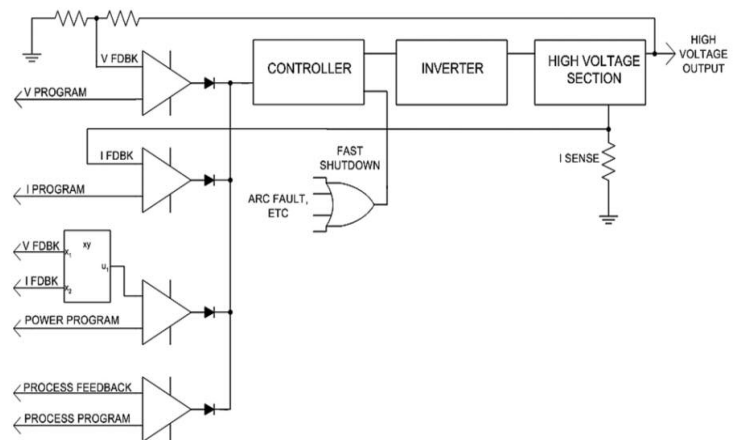


Fig. 3 Power Supply Control Loops

In addition to the voltage and current regulation, other parameters can be precisely regulated. Controlling output power is easily accomplished by an $X \times Y = Z$ function, ($V \times I = W$), 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 effected by the high voltage power supply (i.e. X-ray output, flow rates, etc.).

ARTICLES

High Voltage Power Supplies for Analytical Instrumentation

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. Figures 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 (CR), and the series inductor (LR) 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.

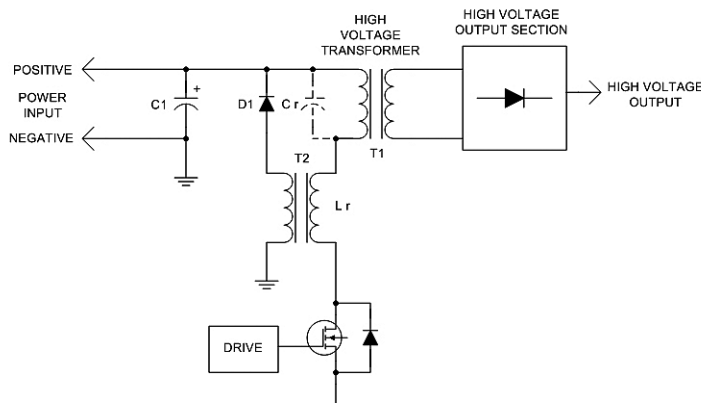


Fig. 4 Resonant Flyback/Forward Converter

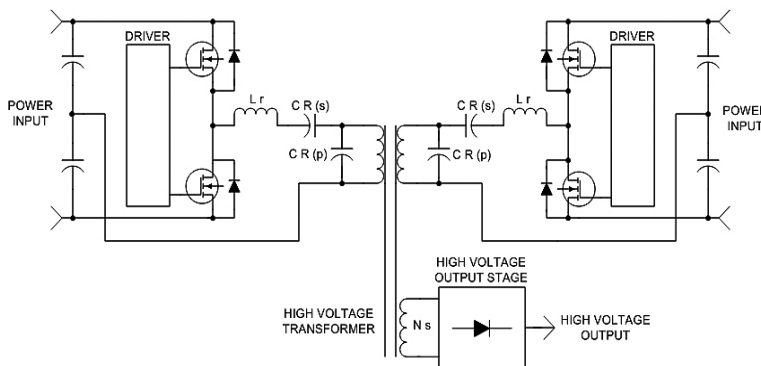


Fig. 5 Half Bridge/Full Bridge

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 have 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)

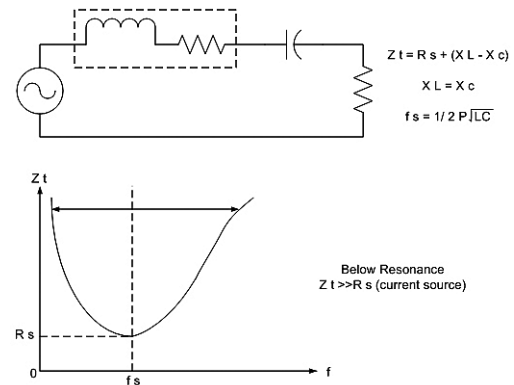


Fig. 6 Series Resonance

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.

ARTICLES

High Voltage Power Supplies for Analytical Instrumentation

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 it is 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, safety aspects of high voltage use requires 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]".

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- 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.

ARTICLES

High Voltage Power Supplies for Electrostatic Applications

High Voltage Power Supplies for Electrostatic Applications

by Cliff Scapellati

ABSTRACT

High voltage power supplies are a key component in electrostatic applications. A variety of industrial and scientific applications of high voltage power supplies are presented for the scientist, engineer, specifier and user of electrostatics. Industrial processes, for example, require significant monitoring of operational conditions in order to maximize product output, improve quality, and reduce cost. New advances in power supply technology provide higher levels of monitoring and process control. Scientific experiments can also be influenced by power supply effects. Contributing effects such as output accuracy, stability, ripple and regulation are discussed.

INTRODUCTION

The use of high voltage in scientific and industrial applications is commonplace. In particular, electrostatics can be utilized for a variety of effects. Broadly stated, electrostatics is the study of effects produced by electrical charges or fields. The applications of electrostatics can be used to generate motion of a material without physical contact, to separate materials down to the elemental level, to combine materials to form a homogeneous mixture and other practical and scientific uses. By definition, the ability of electrostatic effects to do work requires a difference in electrical potential between two or more materials. In most cases, the energy required to force a potential difference is derived from a high voltage source. This high voltage source can be a high voltage power supply. Today's high voltage power supplies are solid state, high frequency designs, which provide performance and control unattainable only a few years ago. Significant improvements in reliability, stability, control, size reductions, cost and safety have been achieved. By being made aware of these improvements, the user of high voltage power supplies for electrostatic applications can benefit. Additionally, unique requirements of high voltage power supplies should be understood as they can affect the equipment, experiments, process or product they are used in.

OPERATIONAL PRINCIPLES OF HV POWER SUPPLIES

The input voltage source may have a wide range of voltage characteristics. AC sources of 50Hz to 400Hz at less

than 24V to 480V are common. DC sources ranging from 5V to 300V can also be found. It is critical for the user to understand the input voltage requirement as this will impact overall system use and design. Regulatory agencies such as Underwriters Laboratory, Canadian Standards Association, IEC and others are highly involved with any circuits connected to the power grid. In addition to powering the main inverter circuits of the power supply, the input voltage source is also used to power auxiliary control circuits and other ancillary power requirements. The input filter stage provides conditioning of the input voltage source.

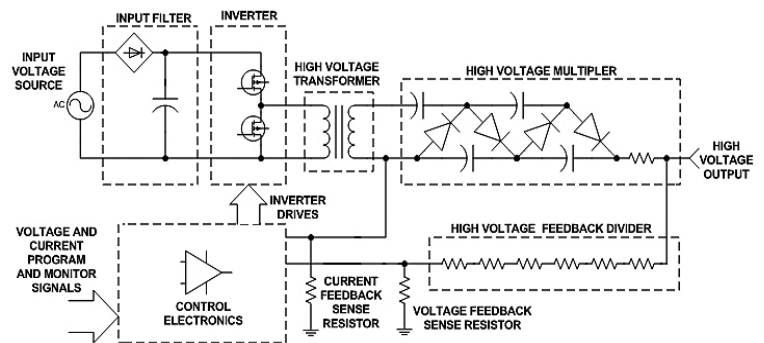


Fig. 1 Simplified Schematic Diagram of a High Voltage Power Supply

This conditioning is usually in the form of rectification and filtering in ac sources, and additional filtering in dc sources. Overload protection, EMI, EMC and monitoring circuits can also be found. The output of the input filter is typically a dc voltage source. This dc voltage provides the energy source for the inverter. The inverter stage converts the dc source to a high frequency ac signal. Many different inverter topologies exist for power supplies. The high voltage power supply has unique factors which may dictate the best inverter approach. 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 ripple reduction 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 as 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 is common-

ARTICLES

High Voltage Power Supplies for Electrostatic Applications

place. The inverter robustness and control loop characteristics must account for virtually any combination of open circuit, short circuit and operating load conditions. These concerns as well as reliability and cost, must be addressed in the High Voltage Power Supply Inverter topology.

The high frequency output of the inverter is applied to the primary of the high voltage step-up transformer. Proper high voltage transformer design requires extensive theoretical and practical engineering. Understanding of magnetics design must be applied along with material and process controls. Much of the specific expertise involves managing the high number of secondary turns, and the high secondary voltages. Due to these 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.

The high voltage multiplier circuits are responsible for rectification and multiplication of the high voltage transformer secondary voltage. These circuits use high voltage diodes and capacitors in a "charge pump" voltage doubler connection. As with the high voltage transformer, high voltage multiplier design requires specific expertise. In addition to rectification and multiplication, high voltage circuits are used in the filtering of the output voltage, and in the monitoring of voltage and current for control feedback. Output impedance may intentionally be added to protect against discharge currents from the power supply storage capacitors.

These high voltage 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 circuits 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. Fig. 2 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 $X \cdot Y = Z$ function, ($V \cdot I = W$), 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 effected by the high voltage power supply (i.e. coatings, flow rates, etc.).

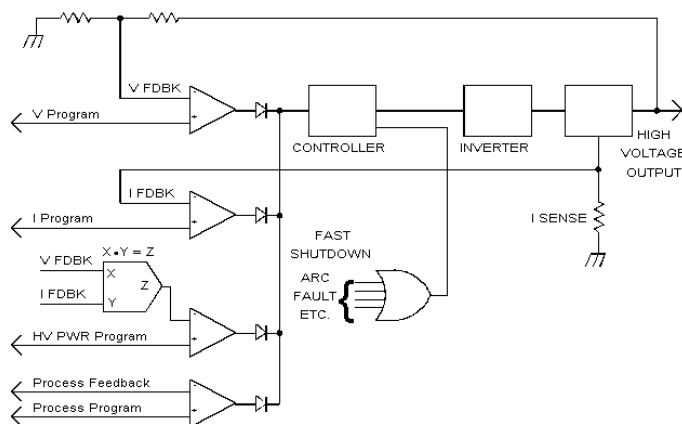


Fig. 2 Power Supply Control Loops

HIGH VOLTAGE REGULATION

The importance of a regulated source of high voltage and/or constant current is critical to most applications involving electrostatics. Variations in output voltage or current can 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.

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 Fig. 1, the high voltage feedback divider consists of a resistive divider network. This network will divide the output voltage

ARTICLES

High Voltage Power Supplies for Electrostatic Applications

to a level low enough to be processed by the control circuits. 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 FUNCTIONS FOR THE HV POWER SUPPLY

In many applications of high voltage, additional control functions may be required for the instrument. The power supply designer must be as familiar with the electrostatics application as the end user. By understanding the application, the power supply designer can incorporate important functions to benefit the end process.

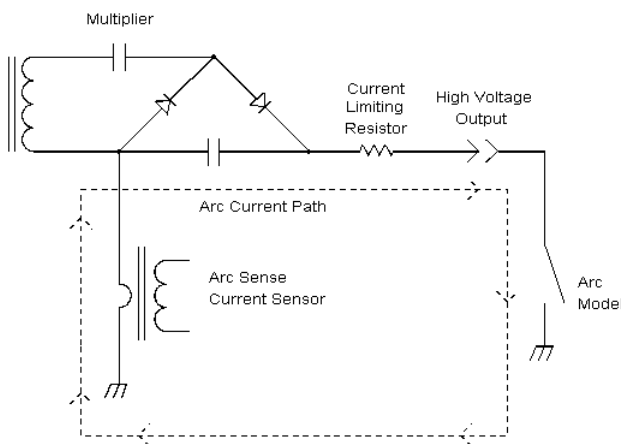


Fig. 3 Arc Sense Circuit

A typical feature that can be implemented into a high voltage power supply is an "ARC Sense" control. Fig. 3 shows a schematic diagram of an arc sense circuit. Typically, a current sensing device such as a current transformer or resistor is inserted in the "low voltage side" of the high voltage output circuits.

Typically, the arc currents are equal to:

$$I = (E/R) \quad (1)$$

where I = Arc current in amperes.

E = Voltage present at high voltage capacitor.

R = Output limiting resistor in ohms.

The arc current is usually much greater than the normal dc current rating of the power supply. This is due to keeping the limiting resistance to a minimum, and thereby the power dissipation to a minimum. Once the arc event is sensed, a number of functions can be implemented. "Arc Quench" is a term which defines the characteristic of an arc to terminate when the applied voltage is removed. Fig. 4 shows a block diagram of an arc quench feature.

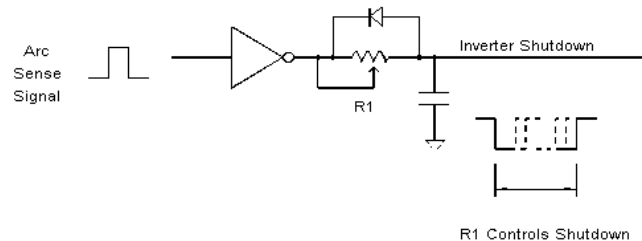


Fig. 4 Arc Quench

If shutdown is not desired on the first arc event, a digital counter can be added as shown in Fig. 5. Shutdown or quench will occur after a predetermined number of arcs have been sensed. A reset time must be used so low frequency arc events are not accumulated in the counter. Example: A specification may define an arc shutdown if eight arcs are sensed within a one minute interval.

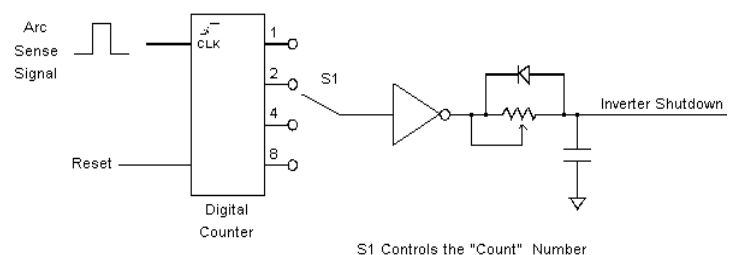


Fig. 5 Arc Count

ARTICLES

High Voltage Power Supplies for Electrostatic Applications

A useful application of the arc sense circuit is to maximize the applied voltage, just below the arcing level. This can be accomplished by sensing that an arc has occurred and lowering the voltage a small fraction until arcing ceases. Voltage can be increased automatically at a slow rate. (Fig. 6).

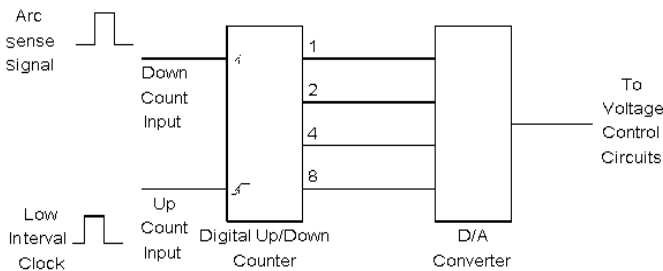


Fig. 6 Automatic Voltage Reduction Circuit

Another feature which can be found in the high voltage power supply is a highly accurate current monitor circuit. For generic applications this monitor feature may only be accurate to milliamperes, or microamperes. However, in some electrostatic applications accuracy down to femtoamperes may be required. This accuracy can be provided by the high voltage monitoring circuits. However, the user of the power supply usually must specify this requirement before ordering.

GENERATING CONSTANT CURRENT SOURCES

In many electrostatic applications, a constant current created by corona effects is desirable. This can be accomplished in a number of unique ways. A constant current source can be broadly defined as having a source impedance much larger than the load impedance it is supplying. Schematically it can be shown as in Fig. 7:

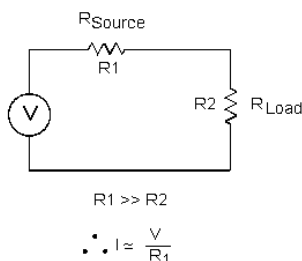


Fig. 7 Practical Current Source

Practically stated, as R2 changes impedance there is negligible effect on the current through R1. Therefore, R1 and R2 have a constant current. In a single power supply application, this can be accomplished two ways. The first is to provide an external resistor as the current regulating device. The second is to electronically regulate the current using the current feedback control as shown in Fig. 2.

In applications where multiple current sources are required, it may not be practical to have multiple power supplies. In this case, multiple resistors can be used to provide an array of current sources. This is typically used where large areas need to be processed with the use of electrostatics. Fig. 8 shows this scheme.

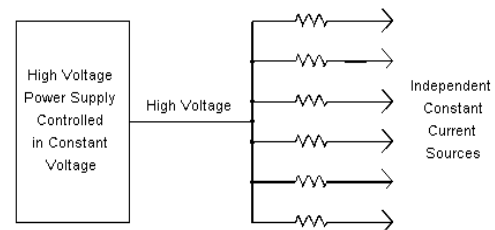


Fig. 8 Simple Multiple Current Sources

CONCLUSION

This paper presented information useful to electrostatic applications using high voltage power supplies. The high voltage power supply has concerns which differentiate it from conventional power supplies. The designer of high voltage power supplies can be a key resource for the user of electrostatics. Significant control features can be offered by the high voltage power supply. In addition, safety aspects of high voltage use requires 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 Voltages and High Power Testing [4]".

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- 1.) C. Scapellati, "High Voltage Power Supplies for Analytical Instrumentation", Pittsburgh Conference, March 1995.
- 2.) D. Chambers and C. Scapellati, "How to Specify Today's High Voltage Power Supplies", Electronic Products Magazine, March 1994.
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- 4.) IEEE Standard 510-1983, IEEE Recommended Practices for Safety in High Voltage and High Power Testing.

STANDARD TEST PROCEDURES

The following pages provide generalized descriptions of the tests used by SPELLMAN HIGH VOLTAGE ELECTRONICS CORPORATION in its Quality Control program. These generalized descriptions cover tests on a large number of different models which vary widely in output voltage, output current, and other operating parameters.

Detailed test data sheets are available for most models. These individual test data sheets delineate the explicit requirements and permissible acceptance levels for each item to be tested. For additional information, please contact the SPELLMAN Engineering/Test Department.

WARNING!

DANGEROUS VOLTAGES MAY BE PRESENT ON THIS EQUIPMENT WHICH MAY BE FATAL.

Make certain all equipment is SECURELY grounded.

Do not touch connections unless equipment is off and internal and load capacitances are discharged.

Do not ground yourself or work under wet or damp conditions.

Failure to follow Safety Procedures may be fatal.

1. PURPOSE

It is the purpose of this procedure to delineate standard tests to be performed on all power supplies manufactured by Spellman High Voltage. It is intended to be used as a stand-alone procedure and in conjunction with other procedures.

2. HIERARCHY

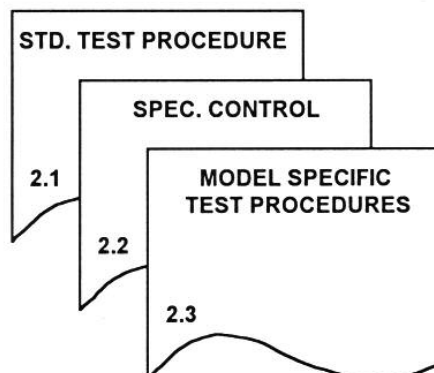


Figure 1. Document Organization

2.1 Standard Test Procedure

Describes generic test to be performed on all power supplies. This combined with the Test Data Sheet provides the parameters for verifying operation of the power supply.

2.2 Specification Control Drawing

Can contain additions or deletions to the standard test procedure.

2.3 Model Specific Test Procedures

Contain elements of both the standard test procedure and the specification control drawing in addition to any detailed instructions needed to verify operation of the supply.

3. HIGH VOLTAGE POWER SUPPLY LOADING METHODS

3.1 Constant Load

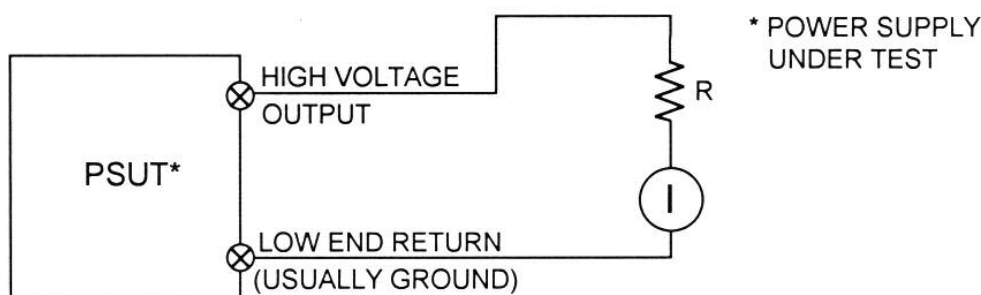


Figure 2. Constant Load Test Set Up

Figure 2 shows a resistor, R , in series with a current meter, I , across the terminals of the P.S.U.T.

CAUTION: The lead from the High Voltage terminal should be high voltage wire. If high voltage wire is not available, ordinary hook-up wire may be used providing reasonable care is exercised to avoid contact with ground circuits.

Resistors must be selected with appropriate voltage and wattage ratings for the specified load requirements. Attention must be given to the physical mounting arrangement, in order to avoid voltage breakdown.

The appropriate current meter, I , should be connected in series with the load resistor, R , in the LOW END RETURN line. This holds the meter at safe, low potentials.

3.2.2 Electron Tube Switch

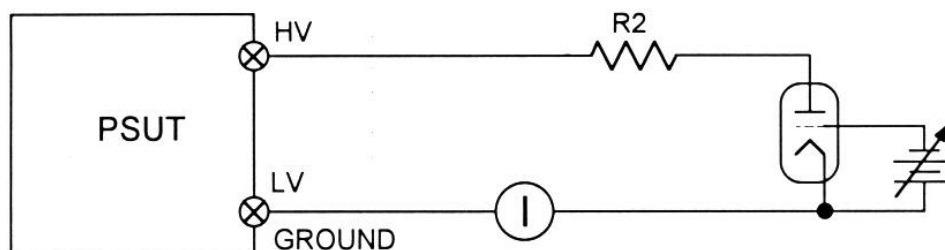


Figure 4. Electron Tube Switch

The circuit of Figure 4 shows a vacuum tube used to cycle the load ON and OFF very quickly. If the grid of the tube is switched from near zero bias to a sufficient negative bias, the tube can be controlled as a switch. Rapidly cycling the load ON and OFF and observing the voltage characteristics is commonly referred to as "Dynamic Load Regulation". Refer to Section 5 for more details.

In addition, the tube can be controlled to provide continuous load adjustment by proper variation of the grid bias. An easy method of attaining bias is by the use of an adjustable cathode resistor.

The manual switch explained in the previous paragraphs are applicable for power supplies with either positive or negative polarity. The electron tube circuit of Figure 4 is shown for a high voltage power supply with positive polarity only. A tube can be used for power supplies with negative polarity by connecting the plate end to low voltage and the cathode end to high voltage. In this case, since the filament and grid supplies will be at high voltage, isolation techniques must be used.

4. VOLTAGE CALIBRATION AND RANGE

This paragraph describes the test set up and method used to measure the output voltage in accordance with the specifications of the specific test data sheet for a given power supply.

Standard Test Procedures for High Voltage Power Supplies

4.1 Test Set Up

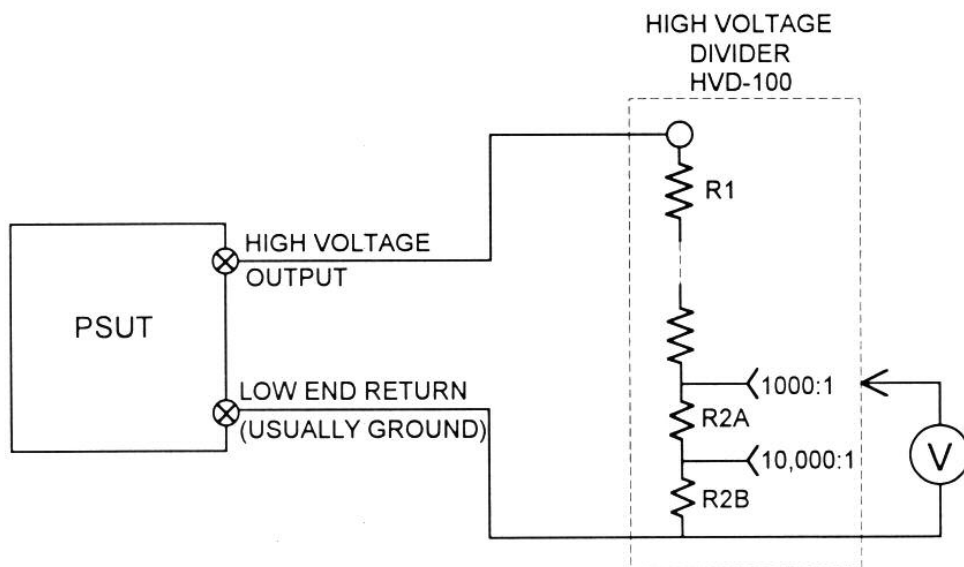


Figure 5. Test Set Up

4.2 Measurement of High Voltage Power Supply Parameters

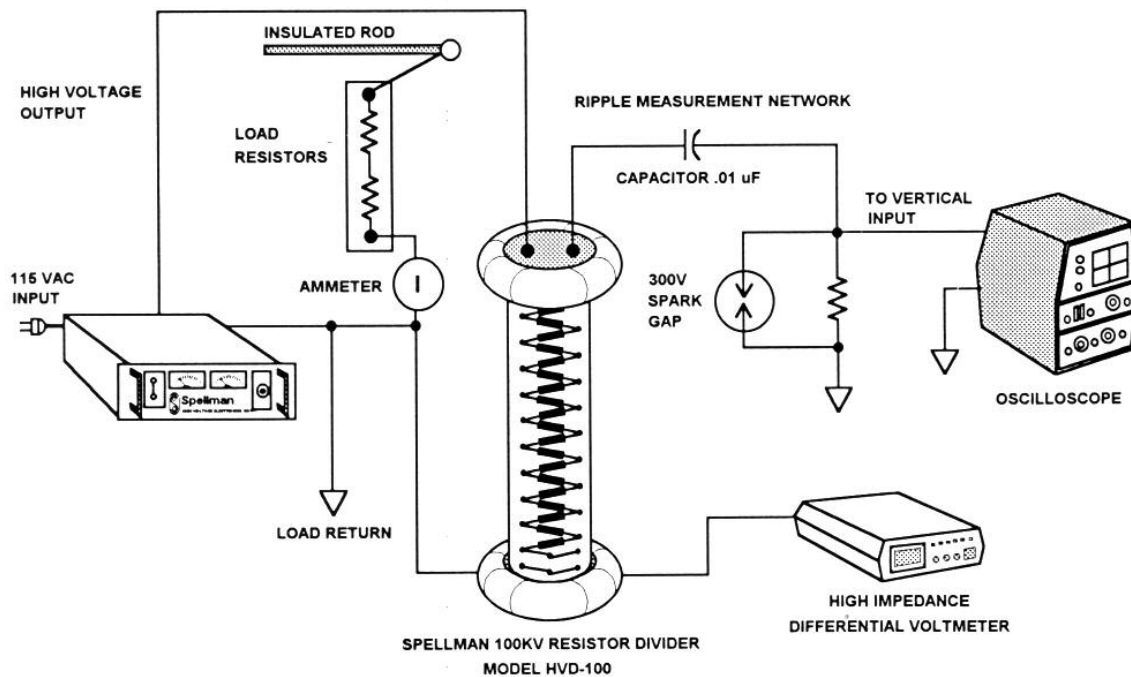


Figure 6. High Voltage Power Supply Test Set Up

4.3 Monitor Instrumentation

The instrument used to measure the divider output voltage must have high input impedance in order to minimize the possibility of introducing errors in measurement due to the loading effects of metering instruments on R2A or R2B (Figure 5). Spellman uses either of two instruments described below for metering (M) in test set-up diagrams, Figure 5 or 6 depending on resolution requirements.

4.3.1 John Fluke Model 8810A

Accuracy of reading including stability: $\pm 0.01\%$ of input
Input impedance: ≥ 1000 Megohms (200mV, 2V, 20V ranges)
Resolution: 10 ppm of range

4.3.2 John Fluke Model 8840A

Accuracy of reading including stability: $\pm 0.005\%$
Input impedance: $\geq 10,000$ Megohms (200mV, 2V, 20V ranges)
Resolution: 1 ppm of range

4.4 Test Method

4.4.1 Connect the HIGH VOLTAGE DIVIDER (HVD) and VOLTMETER as shown in the Test Set-up diagram, Figure 6. The connection between the high voltage output terminal of the P.S.U.T. (Power Supply Under Test) and the high voltage input terminal of the HIGH VOLTAGE DIVIDER should be made with high voltage lead wire.

4.4.2 Connect the P.S.U.T. to a source of input power in accordance with the unit specification. Appropriate input voltage and current monitoring equipment should be included in the test set-up.

4.4.3 All required external adjustment controls should be connected in accordance with the unit specification. Using the specific test data sheet which establishes the proper input voltage conditions and output voltage settings, measure the output voltage according to the above procedures.

4.4.4 Energize the P.S.U.T., exercising reasonable precautions against high voltage hazards.

4.4.5 Measure the output voltage under desired conditions of input voltage and adjustment of voltage controls.

4.4.6 The above measurement is described for what is essentially a "NO LOAD" condition. This is due to the fact that the SPELLMAN High Voltage Divider has an input impedance of 1000 Megohms drawing negligible load current in almost all cases.

Measurements under load may be made as desired by connecting appropriate high voltage load resistors, or other loading devices, across the PSUT, as seen in Figure 6. Current meters should be connected in series with the load resistors in the grounded end to keep the meters at safe potentials. NOTE: See Section 3 for additional information on loading methods.

5. OUTPUT VOLTAGE REGULATION, STATIC AND DYNAMIC

5.1 Definition

In general, most power supply manufacturers in the United States limit the use of the term "regulation" to variations in the output voltage which result directly from changes in the input power source and/or the load resistance.

"Regulation" then, as defined by *Spellman*, and most other manufacturers, specifically *excludes* variations resulting from changes in *temperature* and *time*. Thus, regulation is measured at "constant temperature" and "short" time intervals, where "short" means the time required to make the measurements.

In addition to the two basic components of regulation, i.e. LOAD REGULATION and LINE REGULATION, regulation is further differentiated as STATIC or DYNAMIC variation.

Dynamic regulation is concerned with the output voltage transient response resulting from a line or load change. Of interest are peak deflection and recovery time. *Spellman* defines recovery time as that time required to return from the peak deflection point to within 10% of the new static level. The sketch below details this.

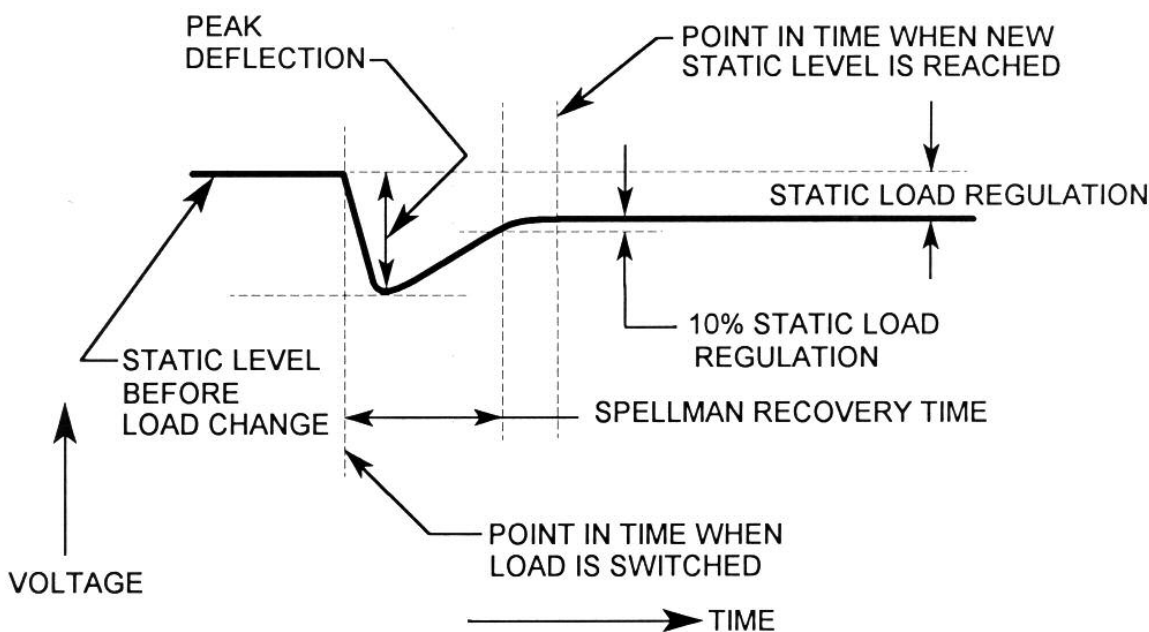


Figure 7. Static and Dynamic Regulation Waveform

5.2 Test Set-Up, *STATIC REGULATION*

- 5.2.1 Connect the output voltmeter circuit as described in Section 4.
- 5.2.2 Connect the PSUT to a source of input power in accordance with the unit specification. Appropriate input voltage and current monitoring equipment should be included in the test set-up. Provide for input power adjustability as required by the specification.
- 5.2.3 Select a loading method (as described in Section 3) which is suitable to the unit specification. Make the necessary connections.

5.3 Test Method, *STATIC LOAD REGULATION*

- 5.3.1 With input voltage maintained constant, make the specified load change using one of the techniques of Section 3.
- 5.3.2 Observe the change in output voltage as read on the voltage monitor. Record for "LOAD ON".
- 5.3.3 Repeat for "LOAD OFF".
- 5.3.4 The above measurements may be made at minimum, maximum and nominal input voltage conditions in accordance with the unit specification. They also may be made at different output voltage conditions, as specified.

5.4 Test Method, *STATIC LINE REGULATION*

- 5.4.1 The same set-up as in Section 5.2 above is used.
- 5.4.2 With output voltage level and load condition set per specification, adjust the input voltage from minimum to maximum.
- 5.4.3 Observe the change in output voltage as read on the voltage monitor. Record.

5.5 Test Method, *DYNAMIC LOAD REGULATION*

- 5.5.1 Connect the output voltage monitor as described in Section 5.
- 5.5.2 With the input voltage maintained constant at its nominal value, establish a square-wave load or pulse load condition as desired.
- 5.5.3 Check that the load current is switching properly by observing the current wave-shape across a current sensing resistor in the "low end" return of the power supply.
- 5.5.4 Observe the dynamic response of the output voltage by using a ripple checker as described in Figure 12.
- 5.5.5 Record the results.

5.6 Test Method, DYNAMIC LINE REGULATION

5.6.1 With load current maintained at a constant level, establish the necessary input voltage switching characteristic.

5.6.2 Observe the dynamic response of the output voltage by using a ripple checker as described in Figure 12.

5.6.3 Record the results.

6. OUTPUT CURRENT REGULATION

6.1 This power supply parameter applies to "Constant Current" or "Current Regulated" supplies. All aspects of "regulation" as described in section 5 above apply here except for the method of measurement.

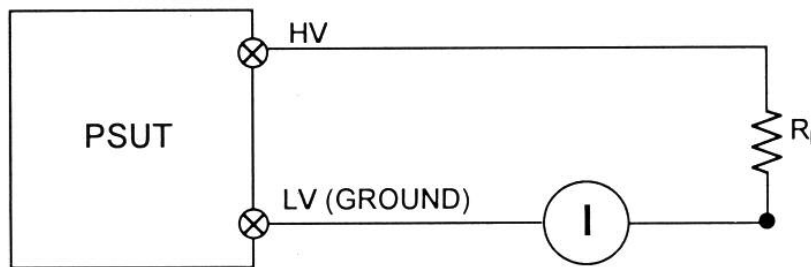


Figure 8. Current Regulation

In Figure 8, the load resistance is represented by R_L . In a current regulated supply, the load resistor, R_L , changes from zero, at the short circuit condition, to some finite value at the rated output voltage condition. The supply cannot maintain regulation into an open circuit, obviously. Thus, load changes are accomplished by "shorting" a portion of the rated load resistor. A current meter, in series with the "low end" of the power supply is used for monitoring the current.

7. CURRENT LIMIT

7.1 This power supply parameter applies to power supplies which although not current regulated, have circuits which will limit the absolute value of the output current.

7.2 Referencing Figure 8, resistor R_L is shorted and the power supply is turned on. The output current is monitored for its peak value and this value is usually 110% of the rated output current.

8. SHORT CIRCUIT

8.1 This test is performed to simulate an arcing condition.

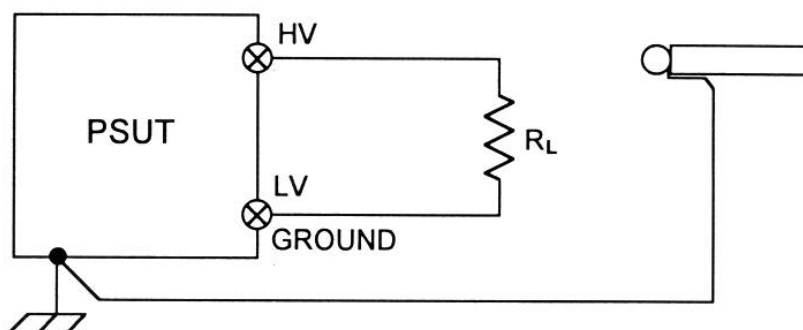


Figure 9. Short Circuit Arcing Test

Using the Plexiglas stick with the conductor connected to ground with a #4 wire, a short circuit condition is applied to the PSUT while the PSUT is energized at full output voltage.

9. INPUT CURRENT

9.1 Input current refers to the current the PSUT draws from its power source (either low voltage DC, or AC mains) during full power operation.

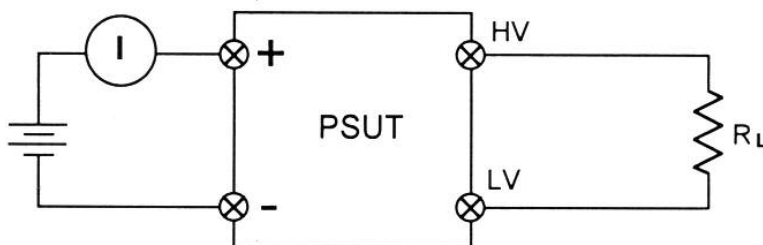


Figure 10. DC Input Current Measurement

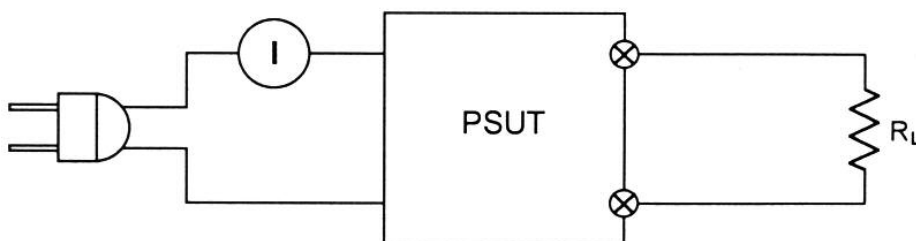


Figure 11. AC Input Current Measurement

A digital multimeter is placed in series with either the positive output of a source or the "HOT" lead of an AC source and the power supply is energized. The parameter is measured at 100% of rated output, at nominal input.

10. RIPPLE

10.1 Ripple Measurement Techniques

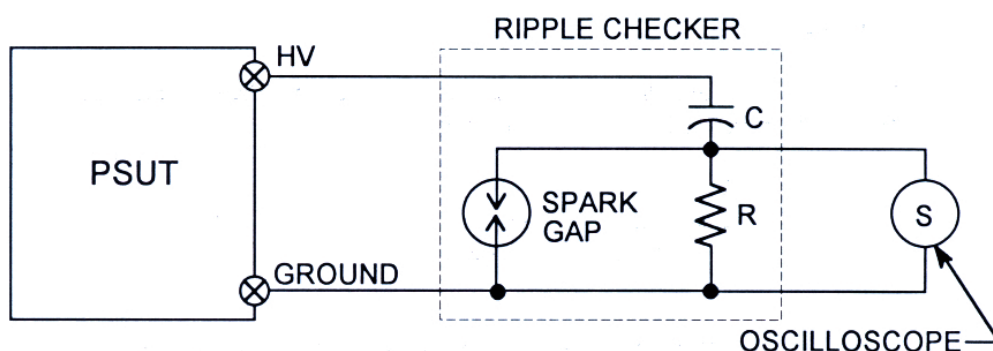


Figure 12. Ripple Measurement

Figure 12 illustrates the technique of using a DC blocking capacitor, C, in series with the power supply output terminal, for the purpose of passing the AC component in the output voltage directly to the oscilloscope, S. Resistor, R, and spark gap, SG, protect the oscilloscope against surges in the output voltage which could be transferred directly through the blocking capacitor to the scope.

The value of C and R must be selected to pass the ripple frequencies of interest with negligible attenuation. The oscilloscope input impedance and frequency response also introduce an error which must be accounted for.

The error in 60 Hz ripple measurements is small for $C \geq 0.01 \mu\text{F}$ and $R \cong 1$ to 10 Megohms. For high frequency components proportionally smaller capacitance values are acceptable.

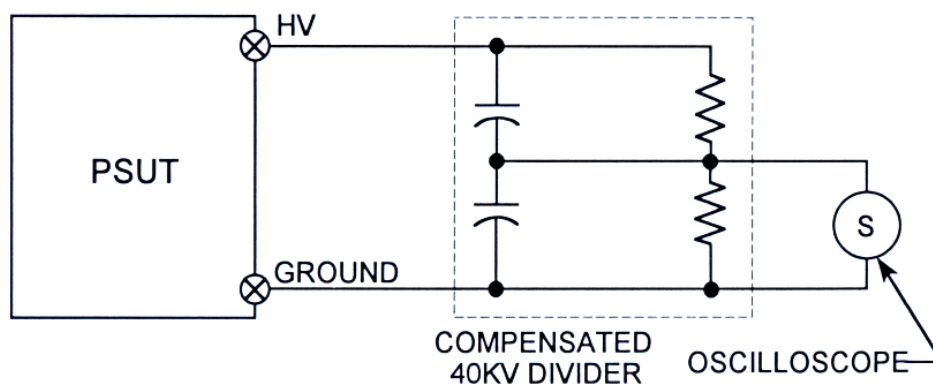


Figure 13 Ripple Measurement

Figure 13 illustrates the use of a compensated 40kV divider for ripple measurements. Although the compensated divider gives an accurate measurement, it suffers from two deficiencies. First, a true no load ripple measurement cannot be made, since the divider itself has 100 Megohms input resistance.

Second, when the power supply output ripple is relatively low, the 1000:1 divider ratio may attenuate the AC component at the divider output to a level which may be difficult to read.

10.2 Test Method

10.2.1 Set all operating parameters as required by the unit specified. These operating parameters must include all the following:

Output Voltage setting
Load Current condition
Input Voltage condition

10.2.2 Read the ripple in peak-to-peak volts on the oscilloscope. Record.

10.2.3 Divide the measured peak-to-peak value by $2\sqrt{2}$ when rms readings are desired (if the ripple is sinusoidal).

ARTICLES

Comparative Testing of Shield Terminations of HV Cables

Comparative Testing of Shield Terminations of High Voltage Cables

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 27-31 May, 2008, pp. 576-579.

ABSTRACT

In HV systems, cable terminations are one of the weakest links. They are especially stressed by the electric field in free space connections. In this light, several termination types for polyethylene HV cables were tested for dielectric strength and leakage current, down to a pico-ampere level. The tested terminations ranged from simple flush cut to graded insulation using non-linear insulation materials. Procedures and results of the testing are described. The dependencies of leakage current on the applied voltage for different terminations are presented. Visual patterns of breakdown are investigated.

The major results are summarized as follows.

- Flush cut shield may have loose strands and presents a danger of the main insulation denting.
- Shrink sleeve dominates the ionization phenomena, effectively suppressing the corona discharge. Its influence is much greater at positive polarity of the shield terminus.
- Shield folded back over an O-ring decreases the electric field, leaves no loose strands and decreases probability of the main insulation damage. It can be recommended for DC applications.
- Stress grading tapes reduce and greatly stabilize leakage current at a level of 1 nA at 100 kV at room temperature, at positive polarity. They are less effective in leakage suppression at negative polarity. They also increase the breakdown voltage that reaches 130 kV at a 15-cm insulation length, at both polarities.

INTRODUCTION

In HV systems, cable terminations are one of the weakest links, whereas the majority of the failures occur at the ground shield side. This side is especially stressed by the electric field in free space connections, which is characteristic for some loads. Field control and rigorous technological processes are key to reliable functioning. The first was realized for a century by stress relief cones in conjunction with solid dielectric fillings. Later, stress-grading non-linear materials in form of paint, tapes and tubes were used with much success (see, e.g., [1]-[3] and their bibliography). In DC applications, which are the main interest of this paper,

it is the falling resistivity-field characteristic that effectively “pushes” the electric field off the shield terminus, where the field is the strongest.

Many works were devoted to the field analysis in cable terminations, both analytical and numerical, in linear and non-linear approaches [1]-[6]. Understandably, they did not address the space charge formation arising from ionization around sharp edges. In fact, most designs avoid fields strong enough to cause ionization. It seems also that no or little work was dedicated to the investigation of leakage current (LC) flowing along the cable termination. In low-current, precision HV applications, these currents may be commensurable with the load current, and being inherently unstable, can compromise the stability. At the same time, low-cost design limits the use of high-quality materials and/or elaborate field control techniques. These limitations are especially important in open-space connections characterized by very unfavorable stress concentration at the shield terminus.

In this light, several termination types for polyethylene HV cables were tested for dielectric strength and LC, down to a pico-ampere level.

EXPERIMENTAL SETUP

Test Rig

The test bench (Fig. 1) comprises a test power supply (PSU) unit with its HV cable T1, Cable Under Test (CUT) T2, and measurement and data acquisition means. Two PSUs (Spellman SL130kV and XRF180kV series) provide smooth voltage regulation and high stability in the range of 0÷130kV, 0÷180kV for positive and negative polarities, respectively. Both HV leads of CUT and that of the PSU cable are connected together, whereas the CUT shield is grounded through a current measuring device. A typical physical implementation is shown in Fig. 2.

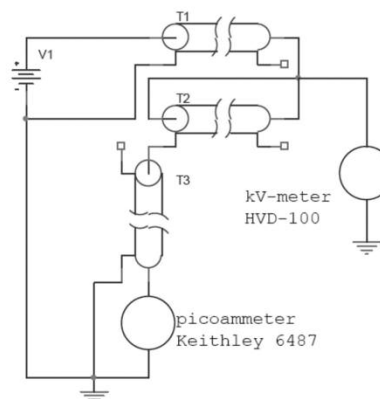


Fig. 1. Schematic layout of test rig.

ARTICLES

Comparative Testing of Shield Terminations of HV Cables

HV leads of all cables were connected physically to the HV electrode of a voltage divider (Spellman model HVD-100) [7] capable of the corona suppressing at the voltage level up to 130kV as shown by electric field analysis. In this way, the LCs generated by the ionization (corona) mechanism at the CUT shield side only are collected and directed through the picoammeter. In order to exclude the current originating at the lead end of the CUT, we screened its shield by a grounded copper electrode.

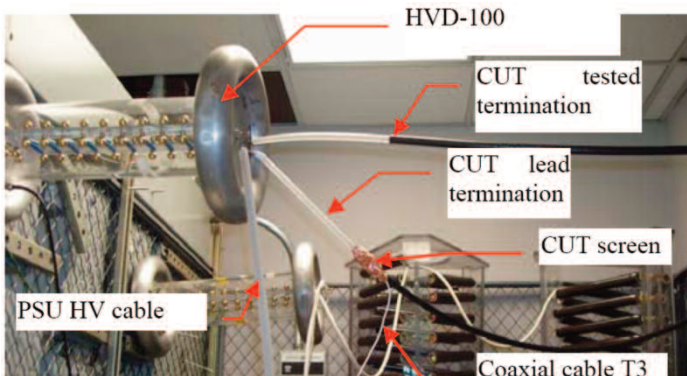


Fig. 2. Experimental setup.

CUTs

Several CUTs using 2124 Dielectric Sciences Polyethylene (PE) cable were manufactured for testing. All of them were approximately 2.5-m-long. Their main parameters are summarized in Table 1, and photos of CUT #4, CUT #6, as examples, are shown in Fig. 3. Acronyms FC and SHT stand for Flush Cut and SHrink Tube, respectively (Alpha irradiated polyolefin SHTs were used). Semiconductive stress grading tape VonRoll 217.21 is SiC-based and as such exhibits a non-linear behavior. Its conductivity increases at higher fields effectively suppressing corona. HiK tape of Dielectric Sciences make is defined as “conductive”. However, its resistivity is infinite when measured at low voltage by DVMs. Its datasheet is unavailable.

CUT designation	Termination method	Termination length l (Fig. 3d), cm
(CUT#1)	FC, no SHT	20
(CUT#2)	FC, SHT	20
(CUT#3)	FC, SHT	14.7
(CUT#4)	O-ring, SHT	14.7
CUT#5	Shield flapped over, tape 217.21	14.7 cm, 3 cm from shield covered by 217.21
CUT#6	Shield flapped over, HiK 6501	14.7 cm, 3 cm from shield covered by tape HiK 6501

Table 1. CUTs description.

Test Procedure

For LC, every cable was tested in steps of, typically, 10kV up to 90kV, and steps of 5kV above 90kV. CUT #6 was not tested at negative polarity. It is important to note that the voltage was changed monotonously, ever increasing. Every test voltage was applied a minute before collecting the LC data that were transferred from a Keithley picoammeter, model 6487, to a PC using a Keithley ExceLINX software. A total of 35 counts were taken at each measurement, which lasted 46 s. The results were averaged over all 35 counts, and the resulting values served for building the volt-ampere characteristics.

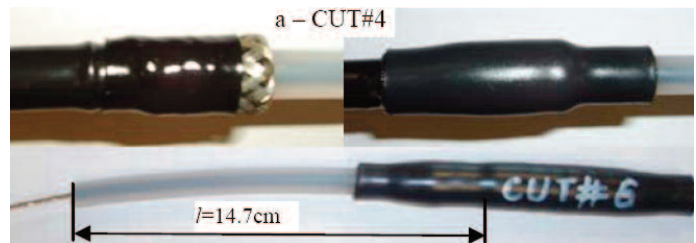


Fig. 3. CUT #4: left - shield flapped over and held by a SHT; right - additional SHT cover. CUT #6 ready for test, SHT 1051727-117 cover on top of HiK tape.

CUT #3 to CUT #6 were subjected to disruptive voltage tests. The voltage was raised at a rate of rise of approximately 2kV/s to breakdown, then brought down to a level by at least 20kV lower than the registered breakdown voltage, and then the test was repeated 2-4 times. In view of the damage sustained by the shrink insulation and semi-conductive tape, we replaced them before testing at the opposite polarity. No averaging or other statistical processing was applied to the disruptive test data. The flashover was videotaped to document the flashover pattern. Experimental techniques and measurement means are described further in the body of the text.

RESULTS OF LEAKAGE CURRENT MEASUREMENT

For setting a baseline, the first experiment was conducted with the flush-cut bare cable CUT #1. The LC was stable in time, especially at positive polarity (grounded shield negative), and reached 40μA at +90kV and 98μA at -90 kV. To ensure that the current did originate at the cable shield, an additional experiment was conducted, in which the FC was protected by a relatively low-curvature electrode. This brought the current down to less than 3μA at +90kV. Covering the shield termination by SHT suppressed the leakage by orders of magnitude (Fig. 5), especially at positive polarity, which also confirms the current

ARTICLES

Comparative Testing of Shield Terminations of HV Cables

origination at the shield cut of the tested termination end. Reducing the length of the bare PE to $l=14.7$ cm in CUT #3 resulted in somewhat higher leakage.

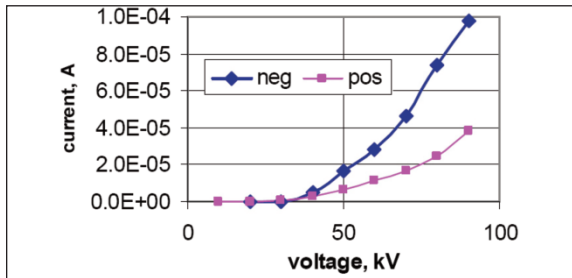


Fig. 4. CUT#1. Leakage current.

Using an O-ring termination (CUT #4) with SHT, at the same length of the bared PE, caused the LC drop by an order of magnitude compared to the flush-cut of CUT #3 (Fig. 6), at both polarities (compare to Fig. 5).

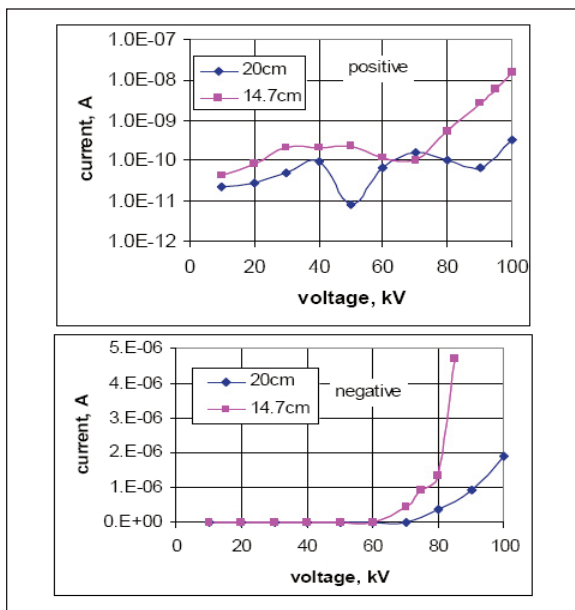


Fig. 5. Leakage current, FC, SHT, CUT#2 ($l=20$ cm PE bared length) and CUT #3 ($l=14.7$ cm) at positive and negative polarity.

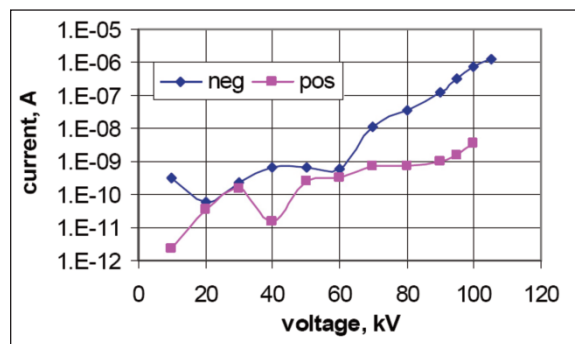


Fig. 6. Leakage current of CUT #4 (O-ring, SHT).

CUT#5 with semiconductive tape (Fig. 7) and CUT #6 with HiK tape (Fig. 8) had the lowest LCs of the order of 1 nA at 100kV at positive polarity. Also, the current was almost burstless: there were practically no instrument overflows at 200-nA range, whereas other cables could be tested at the 20- μ A range only at 100kV. CUT #5 was also tested at negative polarity. The LC was quite large Fig. 9, and even higher than that of CUT #4 (Fig. 6).

DISRUPTIVE VOLTAGE TESTS

The tests were conducted as indicated in Test Procedure Section. At positive polarity, CUT #3 had the first flashover at 104kV along the surface of the test termination. The following breakdowns occurred along the surface of a much lengthier lead termination at 124kV. The path change may be attributed to the shield conditioning by the arc "trimming off" loose strands.

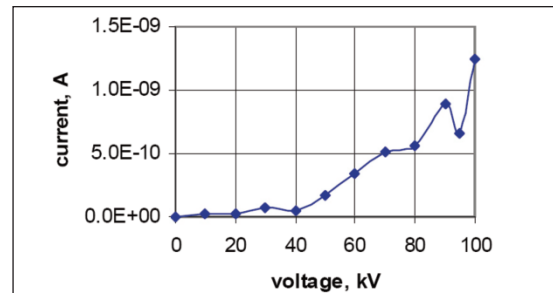


Fig. 7. CUT #5. Leakage current, positive polarity.

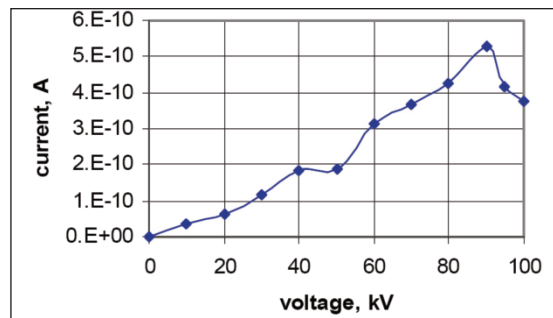


Fig. 8. CUT #6. Leakage current, positive polarity.

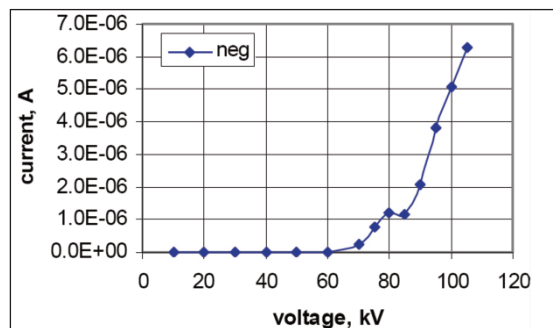


Fig. 9. CUT #5. Leakage current, negative polarity.

ARTICLES

Comparative Testing of Shield Terminations of HV Cables

CUT #4 had a different flashover pattern with the spark bridging the shield and the HV electrode of the HVD-100 through air. First breakdown was at 124.5kV, the consecutive breakdowns occurred at 112kV, 113kV, 117kV. CUT #5, CUT #6 behaved very similar to each other and distinctly different from the other specimens. They broke down at 130kV after ~10s exposure. The first flashover reached the folded end of the shield as indicated by the arrow in Fig. 10.

Consecutive breakdowns occurred at the same voltage, but the luminous channel ended at the shrink sleeve end.

At negative polarity, CUT #4 flashed over the PE surface with the spark anchored at the O-ring. The first breakdown was at 126kV, the consecutive breakdowns occurred at the voltages of 109kV, 104kV, almost identical to the case of the positive polarity. CUT #5 broke down at 136kV after ~5s exposure. The first flashover reached the folded end of the shield as indicated by the arrow in Fig. 10. The second breakdown occurred at the same voltage, but intense corona started forming already at 80kV. The rest of the cables were not tested at negative polarity.



Fig. 10. CUT#5. Photo of flashover.

ANALYSIS AND DISCUSSION

The electric field distribution in cable terminations is strongly non-uniform. It deviates from that given by a field analysis employing constant dielectric and/or conducting properties by virtue of the presence of space and surface charges. Actual distribution at DC conditions is greatly influenced by ionization processes: the field is usually reduced by space and surface charges. Semiconductive tapes act to the same effect, with greater stability and a benefit of the ionization suppression.

As predicted by the field analysis for FC without SHT, the field exceeds 100kV/cm and would lead to air ionization. This is manifested by CUT #1 with exposed shield and erratic short (~1 mm) loose strands protruding from it outwards, which leads to further field enhancement. Large currents drawn from the shield (Fig. 4) are clearly gener-

ated by a mechanism similar to corona; it also may be termed as creeping discharge. The onset of tangible currents was around 30kV for both polarities. In agreement with published data, the corona current is greater at the positive polarity of the shield, or in the convention of this report, at negative polarity. A shrink sleeve, besides weakening the field by virtue of electrostatics, leaves place to but minor ionization in residual air pockets. Charges generated by this mechanism are trapped and neutralize the external field thus suppressing the discharge and greatly reducing the LC. A non-monotonous pattern of the curves is, probably, a result of accumulation and decay of these charges, a process that may have large time constant in view of high resistivity of used dielectrics.

O-ring termination is beneficial for reduction of the external field from purely electrostatic considerations, although its advantage over FC is mainly a guarantee of the absence of loose strands. The O-ring termination was effective at both polarities.

Stress grading tapes have the effect of “pushing” the field away from the shield. At positive polarity, CUT #5, CUT #6 had very stable and low LCs. Their breakdown voltages were considerably higher than the rest of the designs.

At the opposite polarity, the O-ring termination actually performed better in terms of leakage. However, the breakdown voltage of CUT #5 was slightly higher than that for the O-ring termination. In view of only two samples’ testing, a quantitative comparison may be invalid. Nonetheless, the flashover patterns for these designs are very indicative. For both polarities, the flashover followed the short path to the shield with FC and O-ring terminations, but chose the long path in the case of the semiconductive and HiK tapes. The latter pattern means that the field at the shield termination is weakened by the tape, and this tends to yield higher breakdown voltage.

It is our opinion that the stress grading tapes are not necessary for most DC applications but will be a major enhancement for AC and pulsed applications.

As a rule, air gas gaps break down at the same voltage in repetitive tests, except when electrode conditioning, or space charge accumulation, or temperature change take place. In our test, the tendency of lowering the breakdown voltage values in consecutive tests was quite expressed; it has a different mechanism. After several flashovers, the SHTs were punctured and did not suppress LC. It may be that at negative polarity at a voltage, at which LC reaches several microamperes, SHT will be damaged in long run as a result of localized power losses that can be estimated at a subwatt level.

ARTICLES

Comparative Testing of Shield Terminations of HV Cables

The polarity effect on LC for the cables equipped with SHTs was dramatic: at positive polarity, the LC was by three orders of magnitude lower than at negative polarity. We do not have a substantive explanation to this effect. Numerous publications deal with the influence of dielectric barrier on the breakdown voltage of gas gaps, with relation to polarity, barrier placement, kind of gas and its temperature and pressure, etc., but disregard LC. An inference can be made with reference to the influence of space charge on the discharge mechanism in strongly non-uniform gas gaps. On negative polarity (positive shield), negative space charge attracted to the shield enhances the field, whereas at positive polarity, the same charge is repelled and diffused around the shield.

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ARTICLES

Design and Testing of a High-Power Pulsed Load

Design and Testing of a High-Power Pulsed Load

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Presented at 28th Int. Power Modulators Symp., Las Vegas,
 27-31 May, 2008, pp. 181-184.

ABSTRACT

This paper describes the design and testing of a two-channel 52-kW pulsed load. Its main feature is exceptionally low parasitic inductance, on the order of 200nH. Such low inductance was needed in view of microsecond high-current pulses; it was realized by a compact design and careful layout. Small size is a prerequisite for minimizing the inductance; it was achieved by forced liquid cooling. Non-inductive bulk resistors were used at a power rating far exceeding their specifications detailed for operation in air and were found adequate for their mission. They were housed in standard stainless steel drums. The cooling liquid (water-propylene-glycol mixture) was circulated through a heat exchanger.

Multiple aspects of the design are described, including resistor choice, calculating the load inductance, choice of busbars, details of kinematic scheme, heat transfer, HV, safety and other considerations for cooling agents, etc. Special attention was paid to avoiding turbulent flow that could result in the resistor cracking. Inductance measurements showed close correspondence with the calculations. High-power testing showed reliable operation with overheat about 40 K above ambient.

INTRODUCTION

Pulsed resistive dummy loads are widely used in various HV applications, e.g., testing capacitor charger systems, nanosecond and picosecond pulsers, etc. Such loads are characterized by several distinct requirements placing them apart from more conventional DC or AC loads. One of the most difficult requirements is providing low parasitic inductance. It must be of the order of several hundreds of nH, and tens of nH for microsecond and nanosecond applications, respectively. A natural way of minimizing the stray inductance is using low-inductive layouts, preferably, coaxial ones, and minimizing the overall load size. At high average power and high voltage, the latter is difficult to satisfy without effective cooling and keeping proper insulation distances. An additional typical requirement is good

long-term resistance stability; this effectively excludes various aqueous solutions, such as copper sulfate aqueous solutions.

This paper describes the design and testing of a two-channel 52-kW load used in the development of a high repetition rate capacitor charger.

DESIGN

Specifications

The load was designed to the following specifications.

- 1.) Storage capacitance: $C=5.3\mu\text{F}$ (per channel)
- 2.) Max charge voltage: $V_{ch}=1200\text{V}$
- 3.) Max Average power: $P_{av}=52\text{kW}$ (26kW per channel)
- 4.) Pulse width: $t_{pulse}\approx 5\mu\text{s}$
- 5.) Max pulse repetition frequency (PRF): 6kHz
- 6.) Load inductance:
 (per channel, excluding leads) $L_{load}\approx 0.2\mu\text{H}$
- 7.) Voltage reversal (at maximum charge voltage):
 - in normal operation 200V
 - in abnormal operation 600V
- 8.) Possibility of reconfiguration to accept pulsed voltage of several tens of kV.

Circuit Considerations—Choice of Resistance

The test circuit can be represented by a capacitor discharge onto r , L circuit, r , L being the load resistance and inductance, respectively (Fig. 1), the latter including the leads' inductance.

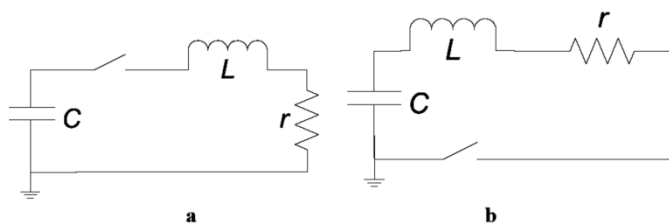


Fig. 1. Equivalent circuit for determining load resistance and inductance.

ARTICLES

Design and Testing of a High-Power Pulsed Load

With zero initial conditions, in Mathcad notation, the load current, i , and the capacitor voltage, v , are given by the formulae

$$i(t, L, r) := \frac{V_0}{L \cdot (\alpha_1(L, r) - \alpha_2(L, r))} \cdot (\exp(\alpha_1(L, r) \cdot t) - \exp(\alpha_2(L, r) \cdot t))$$

$$v(t, L, r) := -\frac{V_0}{(\alpha_1(L, r) - \alpha_2(L, r))} \cdot (\alpha_2(L, r) \cdot \exp(\alpha_1(L, r) \cdot t) - \alpha_1(L, r) \cdot \exp(\alpha_2(L, r) \cdot t))$$

where

$$\alpha_1(L, r) := \frac{-r}{2L} + \sqrt{\frac{r^2}{4L^2} - \frac{1}{L \cdot C}} \quad \alpha_2(L, r) := \frac{-r}{2L} - \sqrt{\frac{r^2}{4L^2} - \frac{1}{L \cdot C}}$$

With the target loop inductance $L=1.5\mu\text{H}$, the voltage reversal of approximately 200 V and $t_{\text{pulse}} \approx 5\mu\text{s}$ are realized with the load resistance $r=0.6\Omega$ (Fig. 2). A reversal of $\approx 600\text{V}$ can be provided by increasing the leads' inductance to $10\mu\text{H}$, or decreasing r to 0.25Ω . Fig. 3 illustrates the capacitor voltage waveforms for non-inductive discharge ($L=0.2\mu\text{H}$) and artificially increased $L=10\mu\text{H}$.

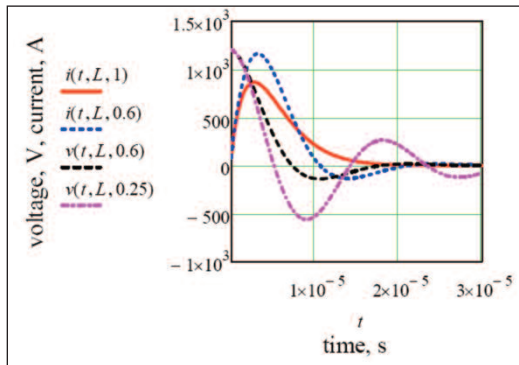


Fig. 2. Current and voltage waveforms for $L=1.5\mu\text{H}$; r values (in Ω) as indicated in variables' legends. $r=1\Omega$ corresponds to critically damped discharge.

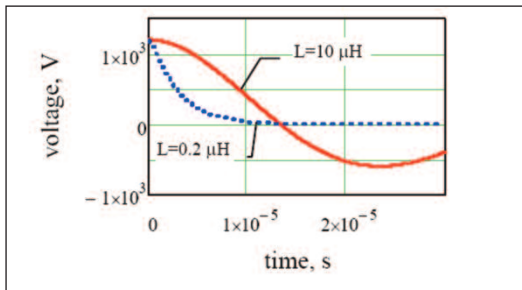


Fig. 3. Current and voltage waveforms for $r=0.6\Omega$.

Realizing the desired resistance and reconfiguring the load is convenient with relatively large number of fixed resistors. Their choice is of prime importance influencing the overall size, cost and reliability. In view of low inductive design, bulk ceramic resistors were chosen. They performed well in nanosecond applications with forced oil cooling [1], which was instrumental in obtaining small size, hence low inductance. Kanthal Globalbar series 510SP slab resistors are relatively inexpensive, compact and easy to mount. The largest parts are specified for the maximum power dissipation of 150W in air; with oil cooling, based on previous experience, we anticipated good safety margin at a 500-W load. A brief testing of 887SP resistors in static transformer oil showed that it was capable of bearing the load of 500-1000W without excessive stress. The main danger, as indicated by the manufacturer, is bringing the cooling agent to the boiling point, which would result in the ceramics cracking. Thus, it is important to avoid turbulent flow in order to decrease the temperature gradients at the boundary.

Finally, $6.3\Omega \pm 20\%$ resistors were chosen. With 48 resistors per channel ($\sim 500\text{W}$ per resistor), the connections are as shown in Fig. 4. The nominal resistance is 0.525Ω , and the measured value is close to 0.6Ω . The load can be re-configured to 2.4Ω , 1.2Ω or 0.3Ω without major changes.

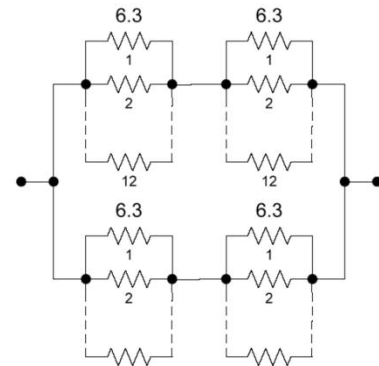


Fig. 4. Electrical connections (one channel).

Mechanical Layout

The load inductance L_{load} is a sum of the resistor assembly inductance and the auxiliary and main busbars' inductances. An equivalent circuit (illustrating also the geometrical arrangement and parasitic resistances) is shown in Fig. 5. According to it, L_{load} can be calculated as

$$L_{\text{load}} = \frac{(L_R + L_{\text{aub}})}{2} + L_{\text{mb}},$$

where L_R is the inductance of the resistor pack of 12, and L_{aub} , L_{mb} are the auxiliary and main busbars inductances, respectively.

Design and Testing of a High-Power Pulsed Load

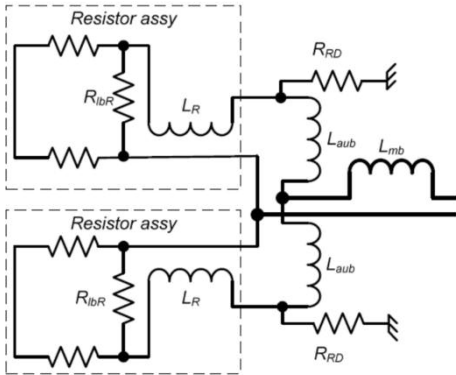


Fig. 5. Equivalent circuit of resistive load accounting for parasitic inductances and coolant conductance.

Minimizing the volume occupied by the magnetic field is key to achieving low inductance. With this in mind the resistors were grouped twelve in parallel in one plane, the return path being provided by another group of twelve (see photo Fig. 6a). The inductance calculation for such an arrangement may be performed for a flat busbar approximation using the following formula [2]:

$$L_{\text{bus}} := \frac{\mu_0}{\pi} \cdot \left(\ln \left(\frac{d}{b+c} \right) + \frac{3}{2} + f \right)$$

where μ_0 is the permeability of free space, d is mean distance between the bars, b , c are the bar thickness and width, respectively, f , ϵ are tabulated values. For the resistor assembly, $d=0.06$ m, $b=0.02$ m, $c=0.3$ m, $f=0.8$, $\epsilon=0.002$, which yields $L=2.5 \cdot 10^{-7}$ H/m, or $L_R=7.5 \cdot 10^{-8}$ H for the resistor pack having a length of ~ 0.3 m. This calculation was also verified by finite element analysis. Since there are two packs connected in parallel, their inductance is halved (see equivalent circuit Fig. 5). The auxiliary and main busbars inductances L_{aub} , L_{mb} add ~ 100 nH, so the overall load inductance was expected not to exceed $200 \div 300$ nH. Actual measurement provided a value of $L=200$ nH (Quadtech 1920 LCR meter, measurement taken at 10 kHz).

The resistor assembly fits into a standard 20-gal stainless steel drum (Fig. 6b) and is suspended by the main busses on a Lexan lid that serves also as a bushing.

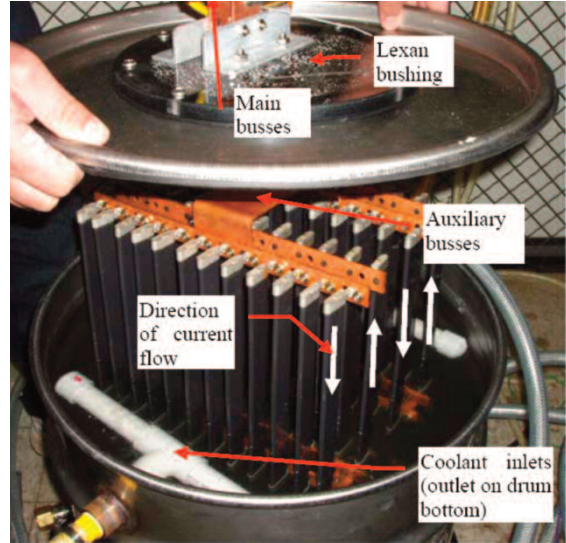


Fig. 6. Resistive load being immersed into coolant (one channel). Load is fully isolated from drum.

Kinematic Diagram

The system works on a closed cycle. The cooling agent is circulated through the two vessels with loads by means of a pump and gives heat away in a heatsink provided by a fan (Fig. 7). The flow is monitored by flowmeters, and the flow rate can be roughly regulated by valves installed on the drums. The hosing system is symmetrical with regard to the loads; no other special means for balancing the load was designed. Overheat condition that may occur following the pump failure, clots, etc., is prevented by interlocking provided by thermostats monitoring the drum temperatures.

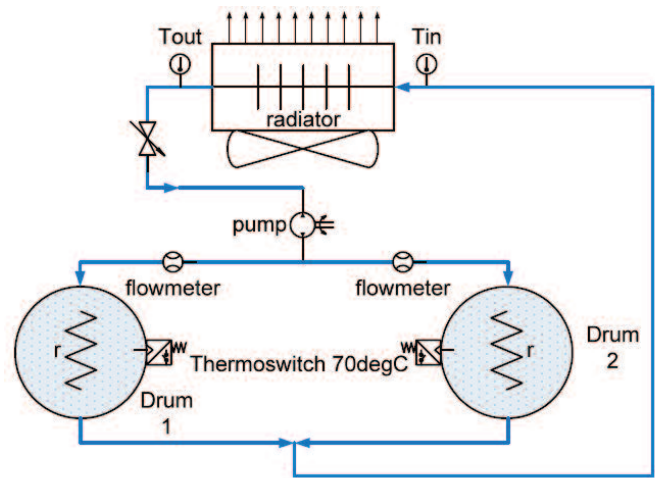


Fig. 7. Kinematic diagram of cooling system.

ARTICLES

Design and Testing of a High-Power Pulsed Load

Cooling Agents

Insulating liquids, such as transformer or silicone oil have good dielectric properties and satisfactory cooling capability, and thus would be an ideal choice. The required flow rate can be calculated using the formula,

$$m = \frac{P}{c_p \Delta T},$$

where P is the dissipated power, $P=52\text{kW}=177,000$ BTU/hr, c_p is specific heat capacity, or just specific heat, at constant pressure, and ΔT is the target temperature difference. Assuming $\Delta T=50^\circ\text{C}$ between the drum and the outlet of the heat exchanger, we calculate the mass flow rate Q_m per channel for oil with $c_p=2\text{kJ/kgK}$ $Q_m \approx 0.5\text{kg/s}$, or the volumetric flow rate $Q_v \approx 30\text{l/min}$ (≈ 8 gal/min). Such flow rate can be easily provided by conventional pumps. However, the problem in using oil is poor safety related to flammability and risk of spillage. Therefore, notwithstanding concerns about dielectric strength and corrosion, we considered Ethylene Glycol (EG), Propylene Glycol (PG) and their water mixtures used widely as antifreezes. Deionized water was discarded in view of expected corrosion and loss of dielectric properties over prolonged service.

EG and its water mixtures have been used in pulsed power (see, e.g., [3], [4]), mainly owing to large permittivity (≈ 40 for EG). For withstanding long pulses (several microseconds and longer) water should be clean, and the solution chilled.

Literary data on resistivity of EG and PG, and especially their solutions, are difficult to find. The only authoritative reference to this property was found in [5]. Some additional information is contained in [6]. According to [5], EG resistivity is $\rho \approx 104\Omega \cdot \text{m}$ at 20°C . A short test was done in-house to estimate this parameter. Two flat electrodes with the area of 7cm^2 , distanced by 0.5mm , were immersed into liquid. A Prestone EG-based coolant (presumably, 97% EG) had $\rho \approx 140\Omega \cdot \text{m}$ at room temperature at a DC voltage of 10V . Deionized water had $\rho \approx 0.7 \cdot 104\Omega \cdot \text{m}$ at 200V , so it was assumed that the mixture would have resistivity not less than that of EG. Curiously, the measured values can be considered favorable in the light of experimental data [7], where the maximum of the dielectric strength for electrolytes, in quasi-uniform fields under the application of long “oblique” pulses, was found at $\rho \approx 2 \div 3.5 \cdot 102\Omega \cdot \text{m}$.

Obviously, the surrounding liquid acts as a shunt for the load resistors. For the described geometry, the coolant shunt resistance (see Fig. 5) may be estimated at 10Ω at room temperature, considerably larger than the resistor

assembly. The temperature rise may decrease this value greatly, by an order of magnitude for $20 \div 30\text{K}$, as inferred from [3], [4].

Analyzing possible load connections Fig. 1, we note that option b, when the load is tied to ground is preferable in that the voltage is applied to the coolant only during the capacitor discharge, and thus the coolant is stressed during several μs only. The parasitic current then flows between the resistor assemblies (resistances R_{lbR}) and between the resistors and the drum (resistances R_{RD})—see Fig. 5. In option a, the voltage across the coolant resides all the time during the charge, when the current flows through R_{RD} , and until the capacitor has been discharged.

We note that in the present implementation our primary concern resides with the resistance stability, and not with dielectric strength: the insulation distances are several centimeters and are ample enough to hold, probably, hundreds of kV at microsecond durations. We do not have substantive information on the dielectric properties of water-glycol mixtures at much longer pulses; however, some useful estimations can be made to this end. The power dissipation in the liquid is,

$$P = \frac{V_{ch}^2}{R_{liq}},$$

or 1MW at $V_{ch}=1200\text{V}$ and $R_{liq}=1.44\Omega$ (see Test Results, following). If applied continuously, such power would bring the mixture to boiling, which can be considered as coinciding with breakdown at long pulses. Thus, the time to breakdown can be estimated as

$$\tau_{brd} = \frac{c_p m \Delta T}{P}$$

assuming adiabatic heating and constant R_{liq} . For the liquid mass $m=70\text{kg}$, $\Delta T=50\text{K}$, $c_p=3.56\text{kJ/kg} \cdot \text{K}$ we calculate $\tau_{brd} \approx 12\text{s}$. Such a situation, although hypothetical in view of the necessity to invest hugely excessive power to sustain the storage capacitor charged, cautions against connection Fig. 1a.

EG is highly toxic, so eventually a Prestone PG diluted by deionized water in a proportion of 50%-50% was chosen as a coolant. PG specific heat of $2.51\text{kJ/kg} \cdot \text{K}$ is close to that of EG ($2.41\text{kJ/kg} \cdot \text{K}$) [8], and in 50%-50% water mixture $c_p=3.56\text{kJ/kg} \cdot \text{K}$, about 85% of specific heat of water. Thus, the flow rate can be considerably lower than that for oil circulation.

ARTICLES

Design and Testing of a High-Power Pulsed Load

TEST RESULTS

Prolonged runs at full power of 52kW showed that the drums' temperature (measured in the midsection using thermocouples) was $60^{\circ}\text{C} \div 70^{\circ}\text{C}$ (depending on ambient temperature and the position of the heat exchanger) at a flow rate of 20l/min. The ambient temperature in the test compartment was maintained by a chiller at 23°C , although the temperature around the drums was considerably higher. No sign of resistors degradation except steel tabs rusting was noted; the coolant, however, became opaque and slimy, and the busbars were also coated with slime. The coolant resistance as measured at high current of up to 3A using a DC power supply varied from 9Ω at 11°C (fresh mixture, kept in the drum for about a month) to 2.8Ω at 18°C (aged mixture), to 1.2Ω at 54°C (aged mixture). This corresponds to the observed increase of the discharge current by $\sim 10\%$ at hot conditions (67°C) compared to cold operation (23°C —see Fig. 8).

Electro-corrosion that is disregarded in short-pulsed systems is an important issue for investigation for this application. However, it is beyond the scope of this paper.

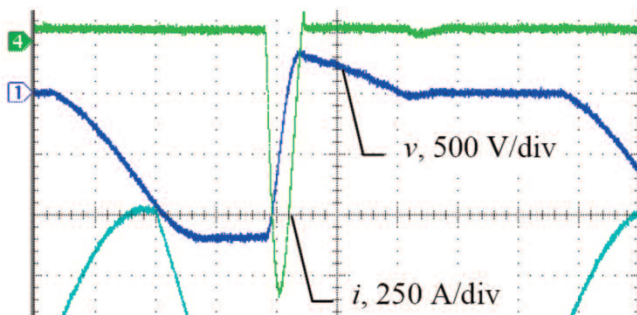


Fig. 8. Capacitor voltage and load current at 23°C .

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ARTICLES

Accurate Measurement of On-State Losses of Power Semiconductors

Accurate Measurement of On-State Losses of Power Semi-Conductors

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ABSTRACT

For safe design, the junction temperature should be kept within the specified range. Three methods are used most often for determining the power losses:

1. Calorimetric method;
2. Using calibrated heatsinks;
3. Electrical measurements of the device voltage and current, and finding the losses by integrating these variables.

The paper concentrates on the third method with the emphasis given to the accurate measurement of the on-state voltage. The techniques of using non-linear dividers with deep voltage clamping are discussed. Novel circuits allowing faithful measurements of the on-state voltage along with good timing resolution of the switching transitions are proposed. Results of circuit simulations are borne out by extensive testing. Examples of measurement of the on-state voltage of large IGBT modules and free wheeling diodes (FWD) are presented. The obtained results are applicable for characterizing various power switches, e.g., gas discharge devices.

INTRODUCTION

For safe design of switch-mode power conversion systems, the junction temperature, T_j , of power semiconductors should be kept within the specified range. A practical method of calculating this parameter is using the following formulae:

$$T_j = T_c + \Delta T_j, \quad \Delta T_j = QR_{th(j-c)},$$

where T_c is the case temperature, T_j is the junction temperature rise over the device case, Q is the component power loss, and $R_{th(j-c)}$ is the thermal resistance, junction to case, specified by the manufacturer. All the indicated temperatures can be readily measured; determining the power losses, involves more effort.

Three methods are commonly used:

4. Calorimetric method (see, e.g., [1]);
5. Using calibrated heatsinks;
6. Electrical measurements of the device voltage v and current i , and then finding the losses E by integrating:

$$E = \int_0^T v i dt,$$

where T is the period. The power loss is found as $P = E/T$, where $f = 1/T$.

The first method provides accurate and most reliable results, but is difficult to implement, especially in air-cooled setups. The second method is simpler but inconvenient for the breadboard setups with ever-changing cooling schemes. We will discuss in more depth the third method as most flexible and understandable for electrical engineers.

Eq. (1) works out well only if the current and voltage measurement are correct. In view of a very large dynamic range of the voltages in the on- and off states, it is difficult to devise a one-stop setup, although there are recommendations how to circumvent this problem [2]. One needs high-quality probes and a good scope; this alone does not guarantee faithful measurements. Ensuring safety is realized with differential probes, at a price of compromising the measurement accuracy in view of their limited bandwidth and capacitive effects.

In determining the switching losses, good time resolution is of prime importance, whereas the dynamic range is less important. For hard switching topologies, these losses may be estimated using the datasheets. In soft switching circuits, the conduction losses dominate, and switching losses may be often neglected. Here the accurate measurement of the on-state voltage comes to the front plan. The following discussion concentrates on this problem.

Basic technique of narrowing the dynamic range is voltage clamping using non-linear dividers (see, e.g., [3]). Fig. 1 shows two examples of such dividers. Implementation a uses N low-voltage diodes connected in series, so when the applied voltage drops below NV_{df} , where V_{df} is the diode forward conduction threshold, there is no current flowing through $R1$, and the voltage at the scope input equals HV_m . Circuit b functions similarly.

ARTICLES

Accurate Measurement of On-State Losses of Power Semiconductors

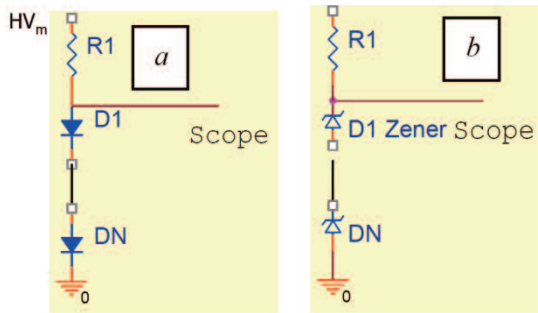


Fig. 1. Schematics of basic nonlinear voltage dividers.

Experimental techniques and measurement means are described further in the body of the text.

SHORTCOMINGS AND LIMITATIONS OF BASIC CIRCUITS

Circuits Fig. 1 depict idealized, and if realized, the ideal devices for measurement of low voltages in high dynamic range. In reality, there are several factors that limit the applicability of these schemes as given in Fig. 1. We skip here obvious component ratings constraints.

One limitation is the inertia introduced by the time constant of the measuring circuit, where $C_p = C_{pr} + C_{pd}$ is the capacitance of the scope input (including the probe), C_{pr} , in parallel with the dynamic capacitance of the diodes/Zener diodes, C_{pd} . Passive voltage probes have typical capacitance of 10pF, so with $R1 = 10k\Omega$, the time constant of the circuit a may be $\sim 10^{-7}$ s, i.e., quite small if the diodes' capacitance can be neglected. However, the diodes remain forward-biased for some time after the voltage HV_m drops below the threshold value, since there is no reverse voltage applied to them. This time may be about 1μs for diodes specified for $trr = 75ns$ recovery, such as BYM26E, as show experiments and PSpice simulations. It takes the diodes $\sim 0.5\mu s$ to come to a non-conducting state, because the reverse current is very small and unable to evacuate the stored charge fast.

Using signal diodes with trr of the order of a few nanoseconds resolves the stored charge problem as show simulations with 1N4500 diodes having $trr = 6$ ns. However, these and similar diodes (in experiments, we used MMBD914, $trr = 4ns$) have significant forward current of tens of μA at tenths of a volt, which translates to a voltage drop across $R1$ of the order of 1V. Thus, large number of diodes should be connected in series to reduce this effect, with some uncertainty remaining.

The capacitance of Zener diodes, on the opposite of the diodes use, must be accounted for, and in this case, the

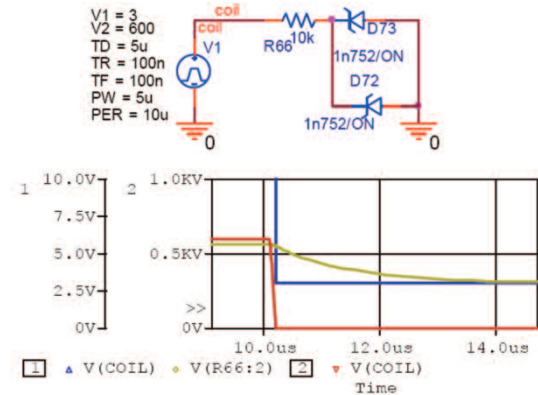


Fig. 2. PSpice simulation of circuit Fig. 1b with Zener diodes. Net aliases in this and following figures show connectivity (e.g., source V1 is connected to point "coil" of circuit Fig. 2).

time constant is on the order of a microsecond. This is larger than typical switching times and commensurable with the pulsewidth at high conversion frequency. Fig. 2, Fig. 3 illustrate this statement. The experiments were conducted with a half-bridge quasi-resonant inverter. A Rogowski coil CWT15 [4] was used for monitoring the components current. Since it is an essentially AC probe, the current traces are usually biased. In Fig. 3, the bias in the emitter current, I_e , was removed numerically.

IMPROVED PRACTICAL CIRCUITS

The detrimental action of the Zener capacitance can be rectified using a fast diode connected in series as shown in Fig. 4 that simulates the actual circuit (except the Zener diodes were 1N751A, and the diode was MMBD914). Simulations Fig. 4 correspond to the measurements of Fig. 5. It is seen that the on-state transition is faster and less noisy compared to Fig. 3. This is important for the loss calculation using (2). We note that a circuit similar to that of Fig. 4 is described in [3], but the actual waveforms exhibit slow $\sim 2\mu s$ transitions, which might be related to the use of an unsuitable diode.

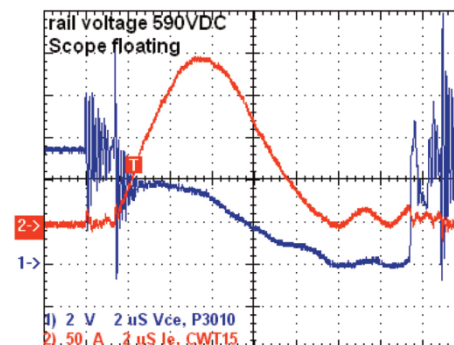


Fig. 3. Measurement of collector-emitter voltage V_{ce} of CM300DC-24NFM Powerex IGBT using circuit Fig. 2. TDS 3024B scope is floating. In this and further plots, waveform notes carry scale information and types of probes used.

ARTICLES

Accurate Measurement of On-State Losses of Power Semiconductors

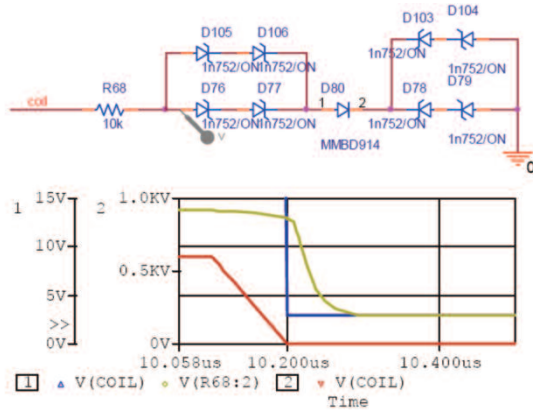


Fig. 4. Blocking Zener diode capacitance using a fast diode. Circuit excited by source V1 Fig. 2.

Although measurements Fig. 5 can be believed to be true in the sense that the voltage between the measurement points was recorded faithfully, the actual Vce voltage is different from it owing to the IGBT internal inductance L_{IGBT}. The inductive voltage drop can be deducted from the measured voltage; a corrected waveform calculated for L_{IGBT}=20nH is shown in Fig. 6.

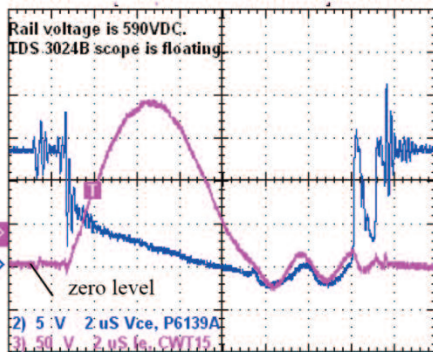


Fig. 5. Measurement of saturation voltage V_{sat} (collector-emitter voltage V_{ce}) of CM300DC-24NFM using circuit Fig. 4. Scope is floating.

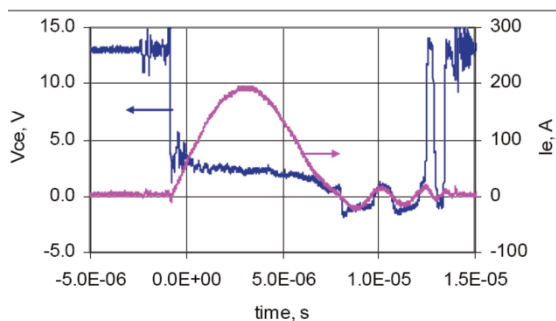


Fig. 6. Vce adjusted for inductive voltage drop (numerical filtering has been applied). It corresponds to CM300DC-24NFM datasheet.

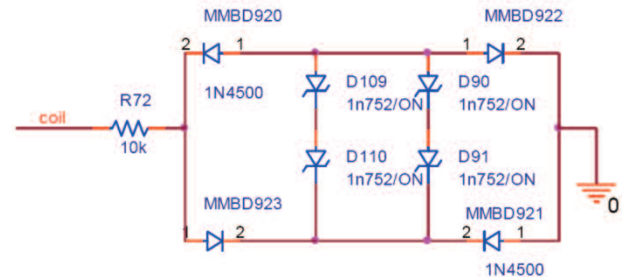


Fig. 7. Bridge formed by fast diodes around a Zener diode works equally well for measurement of positive and negative low voltages in wide dynamic range. Circuit excited by source V1 Fig. 2.

Fig. 8 shows the trace of an IXYS DSEI 2x61 FWD current (one module contains two diodes connected in parallel) together with the voltage trace taken with the divider Fig. 4 (fast diode removed) with the scope floating. The voltage trace has almost a sine wave form with a slow falltime, which is a measurement error caused by the inherent defect of this circuit (Zener diode capacitance).

Using a divider Fig. 7 provides a different picture and is believed to improve the measurement considerably as seen in Fig. 9 that shows also an adjusted waveform and loss curves. Again, the actual forward drop is lower by the inductive component.

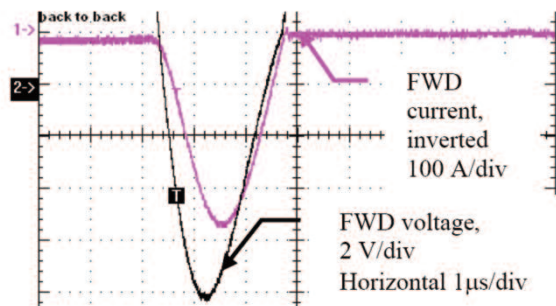


Fig. 8. Trace 2 - Forward drop of FWD IXYS DSEI 2x 61 (negative part). Clamped positive voltage (diode non-conducting) is off-scale. Zener diode capacitance (divider Fig. 4) affects the voltage fall time.

ARTICLES

Accurate Measurement of On-State Losses of Power Semiconductors

They are less “trustworthy” in our opinion than their floating counterparts Fig. 5, Fig. 9 (see also the superposition of the differential and floating measurements Fig. 12), which can be explained by the probe limited bandwidth (25MHz for P5200 compared to 500MHz for P6139A), leads’ capacitance to ground in addition to a 7pF capacitance of each input (estimated 30pF total), and by the large voltage swings (~360V at a rail voltage of 600V) of the inputs relative to ground. Therefore, battery-fed scopes, such as Tektronix TPS series are preferential for this task. Even better, universal, and less expensive solution is using regular scopes fed from an uninterruptible power supply disconnected from mains. Usual safety precautions should be taken in floating measurements.

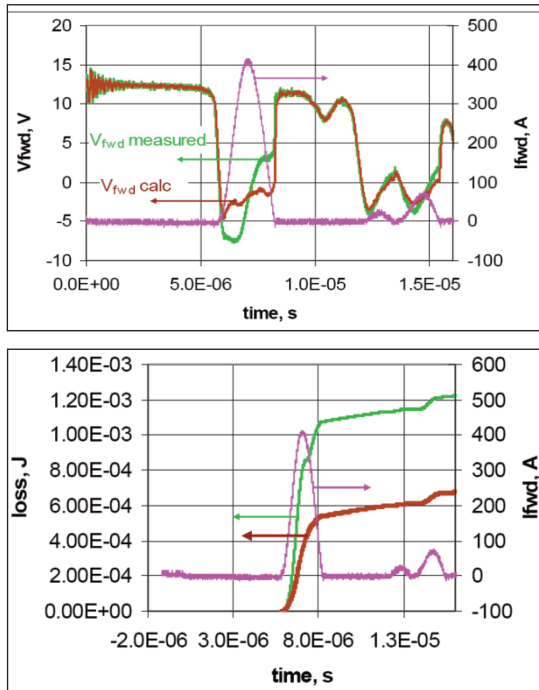


Fig. 9. FWD IXYS DSEI 2x61 losses. Plot a – green trace is measured signal; brown trace is V_{fwd} adjusted for inductive drop L_{dfwd}/dt (diode assembly inductance assessed at 5nH). Green and brown curves plot b match their counterparts in plot a. Divider Fig. 7, Floating scope.

FLOATING OR DIFFERENTIAL MEASUREMENTS?

SAFETY ISSUES

As a rule, the scope chassis is grounded for safety, and floating measurements are performed with differential probes as recommended by scope vendors (see, e.g., [2]). Our experience shows, however, that the quality is severely compromised compared to the case when the scope is floating together with the reference point, e.g., the transistor emitter or the FWD anode. Examples of using a differential probe P5200 for V_{ce} and FWD forward drop measurement are shown in Fig. 10, Fig. 11, respectively.

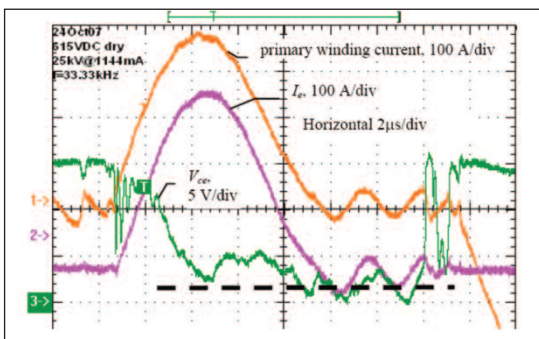


Fig. 10. Differential measurement of V_{sat} (trace 3 V_{ce}) of CM300DC-24NFM Powerex IGBT using circuit Fig. 4. Trace 3 may have some offset, likely zero is shown by dashed line.

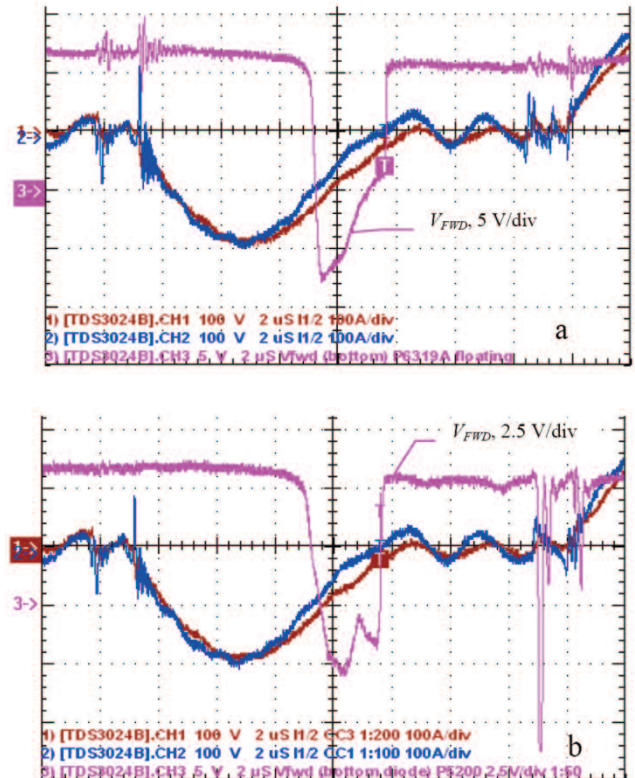


Fig. 11. Trace 3 - Forward drop of FWD IXYS DSEI 2x 61, two modules in parallel. a – high-bandwidth P6139A probe, b - differential probe. Both measurements taken with floating scope.

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Accurate Measurement of On-State Losses of Power Semiconductors

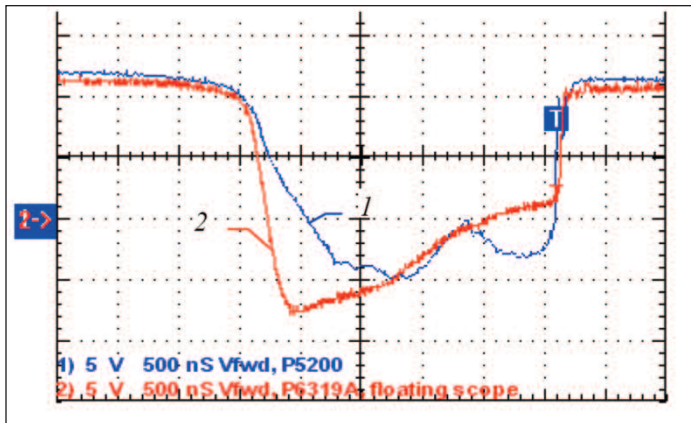


Fig. 12. Superposition of differential and floating measurements of Fig. 11a, b.

CONCLUSION

Divider Fig. 4 is recommended for the measurement of the on-state voltage of large power switches. Clamping voltage should be adjusted to the expected on-state value using proper number of zener diodes. Floating measurements provide better accuracy, however, safety rules should be strictly observed.

ACKNOWLEDGMENT

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ARTICLES

Highly Efficient Switch-Mode 100kV, 100kW Power Supply for ESP Applications

Highly Efficient Switch-Mode 100kV, 100kW Power Supply for ESP Applications

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 21-24 Oct., 2008, pp. 284-288.

ABSTRACT

For nearly a century, electrostatic precipitators (ESP) were driven by line-frequency transformer-rectifier sets. The last decade has been marked by steady penetration of high-frequency HV power supplies (HVPS) that offer considerable benefits for the industry.

This paper describes a novel concept and physical demonstration of an ultra-high efficiency, small size and low cost HVPS specifically designed for ESP and similar markets. Key technology includes a modular HV converter with energy dosing inverters, which operate at above 50kHz with and have demonstrated an efficiency of 97.5% in a wide range of operating conditions. The inverters' output voltages are phase-shifted, which yields an exceptionally low ripple of 1% and a slew rate of 3kV/μs combined with low stored energy. Modular construction allows easy tailoring of HVPS for specific needs. Owing to high efficiency, small size is achieved without turning to liquid cooling. Controls provide standard operating features and advanced digital processing capabilities, along with easiness of accommodating application-specific requirements.

HVPS design and testing are detailed. Experimental current and voltage waveforms indicate virtually lossless switching for widely-varying load in the full range of the line input voltages, and fair agreement with simulations. Calorimetric measurement of losses indicates to a >98.5% efficiency of the HV section. The overall efficiency is 95% at full load and greater than 90% at 20% load, with power factor typically greater than 93%.

KEYWORDS

Electrostatic Precipitator, ESP Power Supplies, High-Frequency Power Supplies, voltage multiplier

INTRODUCTION

For nearly a century, ESPs were driven by line-frequency transformer-rectifier sets. The last decade has been marked by a steady penetration of high-frequency HV power supplies (HVPS) that offer considerable benefits for the industry: small size, low ripple, fast response, etc., fa-

cilitating better collection efficiency. A good overview is provided by [1], [2]. It was noted that Alstom and NWL lead the market with hundreds of fielded units. Between other developments, work of Applied Plasma Physics [3], Genvolt [4], VEI [5] should be mentioned.

High conversion frequency, typically 20-25kHz facilitates the size reduction. As noted in [2], the HV transformer of the Alstom SIR weighs about 22 lb, or 1/15 of that for a 60Hz power supply. Other passive components are shrunk respectively.

Heat management is one of the main issues for reliability. It is done by air-cooling (NWL) or liquid cooling (Alstom). It should be noted that air-cooling schemes seem to be preferential in this industry. In order to realize high efficiency, almost universally, the converter part of the above HVPS makes use of series resonance to avoid switching losses. The theory and practice of such converters is known well [6], [7]. A natural way for the voltage/current adjustment in such converters is frequency regulation. Audio noise is not an issue for the ESP and similar applications.

This paper describes a novel concept and physical demonstration of an ultra-high efficiency, small size and low cost HVPS specifically designed for ESP and similar markets.

MAIN SPECIFICATIONS

- 1.) Average output power 100kW in the output voltage range of 90-100kV; derated at lower voltage
- 2.) High frequency ripple component: 1% typically at 100kV, full power.
- 3.) Dynamic Response: slew rate 100kV/ms min (5% to 9 5% of preset voltage). Typically 300kV/ms
- 4.) Output Stored Energy: < 10 J.
- 5.) Conversion frequency 50kHz
- 6.) Input Voltage: Three Phase 400VAC +10%, -14%
- 7.) Power Efficiency: typically > 95% at full power at 100 kV, > 90% at 20kW.
- 8.) Power factor: > 93% at full power at 100kV, > 75% at 20kW.
- 9.) SPARK/ARC WITHSTAND
- 10.) Overall weight 250kg TBD; HV unit 109kg (240 lbs); Oil volume less than 60 liter

ARTICLES

**Highly Efficient Switch-Mode 100kV, 100kW
Power Supply for ESP Applications**
KEY TECHNOLOGY

The HVPS is built around a modular HV converter (Figure 1). All converter modules M1-MN are fed from a common Input Rectifier (IR). The modules comprise inverter INV1-INVN feeding HV transformers T1-TN that feed voltage multipliers R1-RN, which voltages are summed by their DC outputs. Such topology may be termed as “inductive adder”. For the 100kV, 100kW rating N=4. Each module is built for 25kV, 25kW average power and must have high potential insulation of the secondary winding of the transformer rated at 3·25kV=75kVDC. This insulation must also withstand transient voltages arising during the HVPS turn-on and turn-off. The number of such transients is determined by the HVPS operating scenario, and mainly by the sparking rate.

The topology Figure 1 was investigated long ago. It allows reduction both of the number of the multiplier stages and the voltage rating of the HV transformer. The first improves the compression ratio and reduces drastically the stored energy. Phase shift of the inverters’ outputs voltages results in the decrease of the output ripple and in additional reduction of the stored energy. In this approach, the development costs and time are driven down noting that once a single module has been developed (including its main insulation), the whole system is realized by a simple combination of the desired number of modules. The penalty is larger part count and the necessity of high-potential insulation that is not required in conventional Cockcroft-Walton multipliers. However, this insulation is subjected mainly to DC stresses and therefore ages much slower compared to an AC stress.

The converter cells are centered around half-bridge energy dosing quasi-resonant inverters (Figure 2) [10], [11], [12]. The principle and theory of operation were put forward in [11]. In normal mode, one of the divider capacitors, Cdiv, is charged to the rail voltage. When the corresponding switch closes, it discharges through the primary, while its counterpart recharges to the rail voltage. If the current path contains an inductance, a sine waveform is generated, and ideally, all the energy stored in Cdiv would be transferred to the secondary side. If Cdiv discharges fully, and the current does not fall to zero, the free-wheeling diodes (FWD) across the capacitors clamp the current preventing the voltage reversal. Thus, the remainder of the energy stored in the circuit inductance is transferred to the output (see also Figure 4). The benefits of this topology are tight control of the energy transfer and inherent limitation of the short circuit current and voltages across the converter components.

The maximum frequency, at which the operation is possible with zero-current crossing (ZCC), in a normalized form, is given by the equation

$$f_N = \frac{1}{\frac{2}{\pi} \left[\frac{1}{2} a \cos \left(\frac{V_l}{V_l - E} \right) + \frac{E}{2V_l} \sqrt{1 - \frac{2V_l}{E}} \right]}$$

where E is the rail voltage, and both the rail voltage and the load voltage V_l are referenced to the same side of the transformer. The conversion frequency f is normalized to the resonant frequency f_0 of the loop formed by the leakage inductance and resonant capacitors:

$$f_N = \frac{f}{f_0}$$

A sample plot of this equation is shown in Figure 3. It should be noted that the real conversion frequency is somewhat lower to allow a deadtime of ~1.5μs.

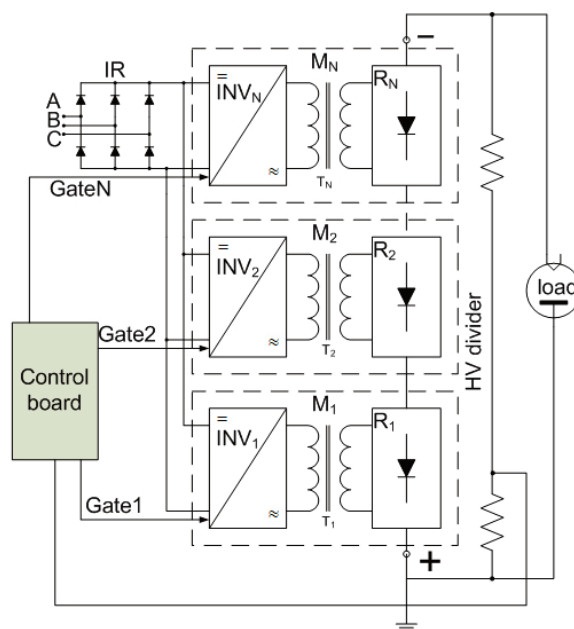


Fig. 1. HVPS block-diagram.

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Highly Efficient Switch-Mode 100kV, 100kW Power Supply for ESP Applications

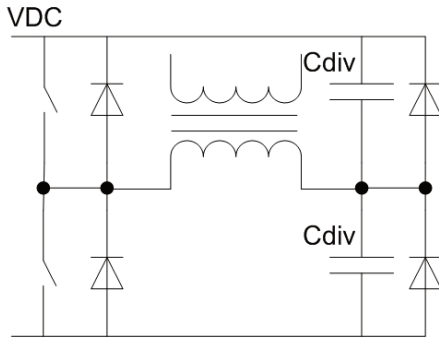


Fig. 2. Inverter with energy dosing capacitors

The inverters operate at approximately 50kHz at full load with virtually zero switching losses. The leakage inductance of the HV transformers is fully incorporated into the resonant tank circuits, so no external inductors are necessary. Besides lowering the part count and cost, this feature is highly beneficial for the chosen multicell resonant topology, since leakage inductance is well repeatable from sample to sample and does not depend on temperature. Controls provide standard operating features and advanced digital processing capabilities, along with the easiness of accommodating application-specific requirements. The output regulation is accomplished by the frequency control.

EXPERIMENTAL

Single module

Typical waveforms shown in Figure 4 (taken at nominal line) indicate good resonant switching with no shoot-through currents in the full range of the line input voltages, and fair agreement with PSpice simulations. The primary winding was divided into two sections connected in parallel, each commutated by a transistor set, hence the notation “halved” in the figure caption. The dashed line shows the start of the FWD conduction. At low line, the FWDs do not conduct, and the converter operates in a boundary mode given by (*). These measurements were conducted with the Powerex IGBTs CM300DC-24NFM. The power losses were assessed at 50W per transistor (four transistors, or 800W per converter module), and the heat was easily evacuated using air-cooled heatsinks with overhear above ambient of less than 40°C. The methods of power loss measurement are detailed in [13].

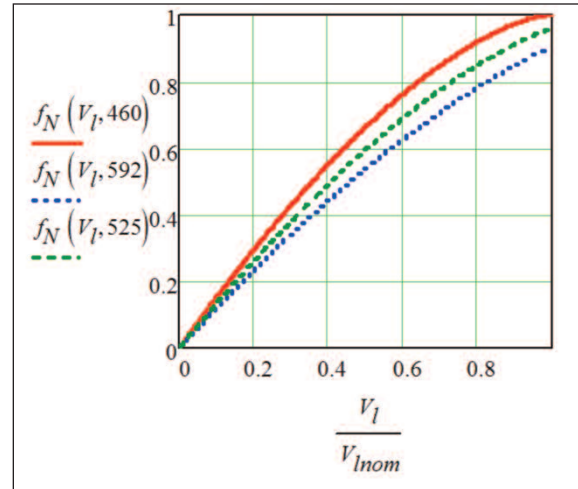


Fig. 3. ZCC curves for low (460V), high (592 V) and nominal (525V) DC rail voltages. V_{lnom} is nominal load voltage.

Special attention was paid to the determination of the HV transformer and multiplier losses. This was key to the design of the HV tank. With this purpose, calorimetric measurements of the losses were performed. They yielded a figure of 344W, with 175W attributed to the transformer losses, and the rest to the multiplier losses. Thus, the efficiency of the HV section was expected to be >98.5%. Accounting also for the inverter losses, the converter efficiency was estimated at 97.5%, so the overall efficiency of 95% of the whole HVPS was projected. In view of the expected high efficiency, it was decided to adopt an air-cooling scheme.

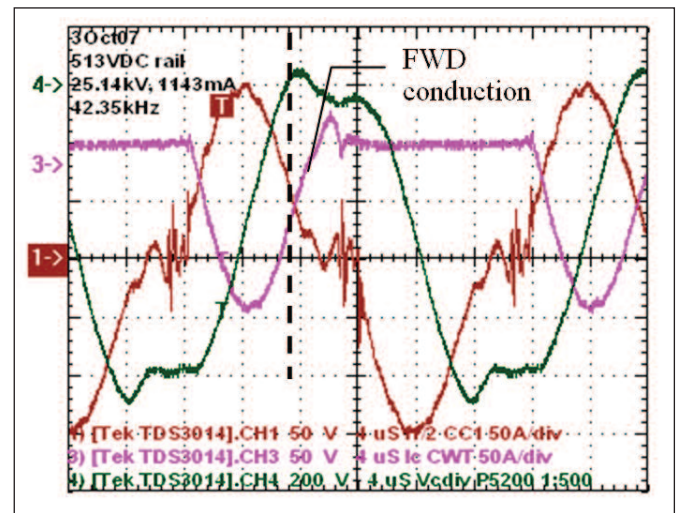


Fig. 4. Nominal line. $P=28.7kW$. trace 1 – primary winding current (halved); trace 3 – collector current (halved); trace 4 – voltage across resonant capacitors. FWD conducts to the right of dotted line.

ARTICLES

Highly Efficient Switch-Mode 100kV, 100kW Power Supply for ESP Applications



Fig. 5. Laboratory HVPS.

HVPS Tests

A laboratory HVPS was assembled on a cart as shown in Figure 5. It comprises three main units: a circuit breaker protected line rectifier, an inverter section and an oil-filled HV tank. We note that in this work, the emphasis was on the converter part; the line rectifier was not optimized.

The HVPS was extensively tested with resistive loads. Figure 6 and Figure 7 show typical phase-shifted primary windings currents (halved) for 100kW and 50kW operation, respectively. The oscillations after the main current surge are generated by the resonance between the leakage inductance and parasitic capacitance of the transformers. Note the absence of the “backswing” current pulse characteristic for the series resonant schemes under light load.

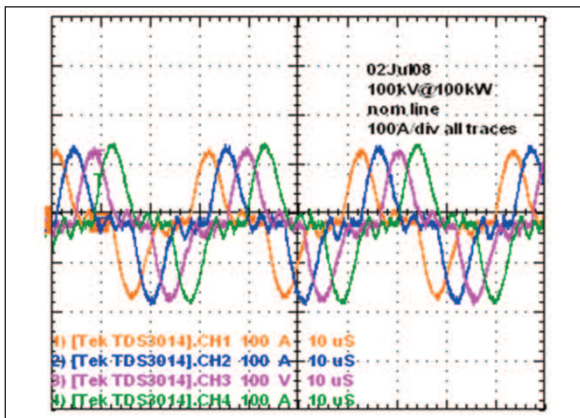


Fig. 6. $\pi/4$ -phase-shifted primary windings currents (halved) at 100kV@100kW. Nominal line voltage 400 VAC.

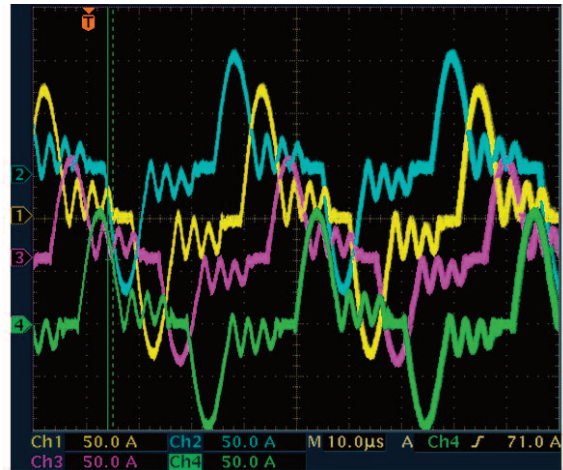


Fig. 7. Same as in Figure 6 at 100 kV@50 kW. Low line 400 VAC-14 % (345 VAC).

Since the full-wave rectification scheme is used, the phase shift is $\pi/4$. PSpice calculations predict 0.223% output voltage ripple peak-to-peak (p-p) with the HVPS shock capacitance of $<2\text{nF}$ (Figure 8) at the worst case of high line; the measured ripple is roughly four times larger, and has a lower frequency fundamental component (Figure 9), which can be attributed to the asymmetry of the gate signals, unequal parasitic capacitances, spread in winding data, etc. Similar effect was observed in [9]. These simulations provide also a value of the Power Factor (PF) of 0.943, which is close to the experimental results.

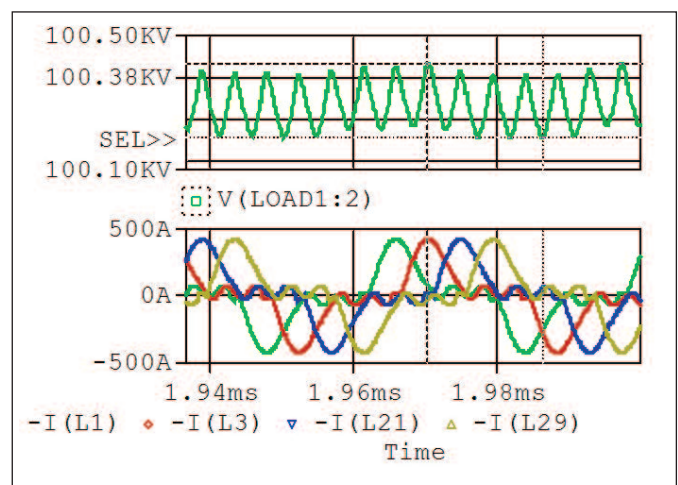


Fig. 8. HVPS circuit simulation. High line 580V. ripple 0.223% p-p. PF=0.943. Experimental PF= 0.946 (see Figure 11).

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Highly Efficient Switch-Mode 100kV, 100kW Power Supply for ESP Applications

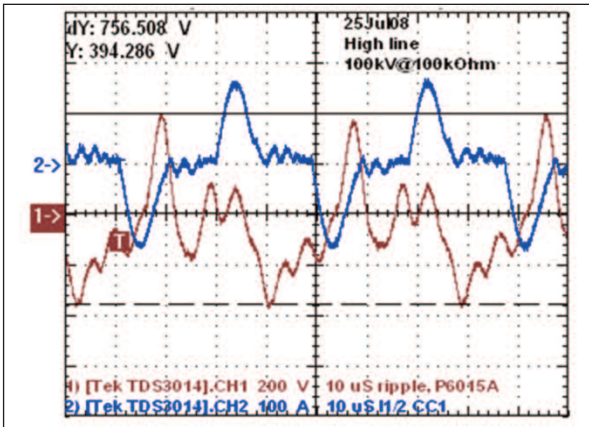


Fig. 9. Ripple at 100 kV across 100-kΩ load is 0.762 % p-p.

The dynamic response of the HVPS is exceptionally fast: the risetime from zero to full output voltage is typically less than 250 μs (Figure 10), depending on the line voltage. With fair accuracy, the dynamic characteristics can be analyzed using the equation

$$V_L(t) := 2 \cdot V_{rail} \sqrt{\frac{C_{div}}{C_s}} \cdot f \cdot t$$

where all the variables and parameters are reflected to the same side of the transformer; C_s is the overall capacitance of the module multiplier. If the frequency is varied during the charge, PSpice simulations provide much better accuracy.

Fast response is beneficial not only for ESP but medical applications as well. We note that the risetime practically does not depend on the load, since the load current is by an order of magnitude smaller than the current charging the multiplier capacitors.

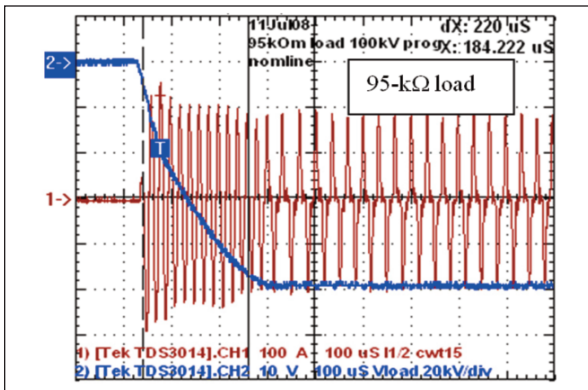


Fig. 10. Risetime across 95kΩ load at nominal line. Trace 2 – load voltage, 20kV/div; trace 1 – primary current (halved), 100 A/div.

Figure 11 presents experimental data on the power measurements obtained at nominal line. In accordance with the simulations and information derived from the work with sin-

gle module, the overall efficiency is 95% at full load and greater than 90% at 20% load. The power factor was also satisfactorily high (compare to the simulation Figure 8). At high and low line, the measurements yielded very similar results. At higher resistance load, the efficiency and PF also stayed high (Figure 12).

At the time of writing this paper, long-term runs at 100kV have been performed up to a power level of 75kW. Full-power tests were limited to ~40 min. They showed conservative overheating of the major HVPS components. For the nominal line, the results are summarized in Table 1.

load power, kW	transistor baseplate	FWD baseplate	HV tank
75	20	18	27
100	25	23	N/A

Table 1. Overheat of major HVPS components, °C.

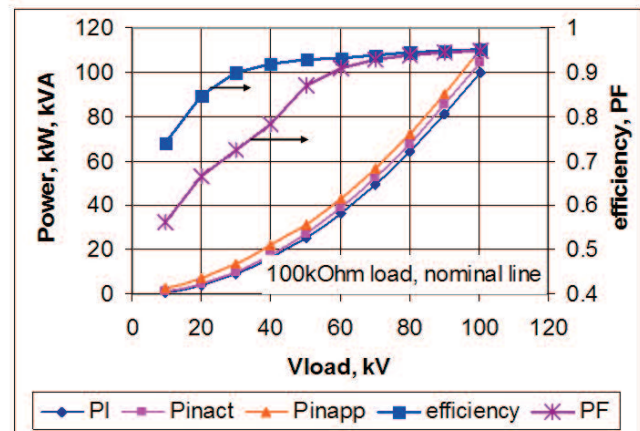


Fig. 11. Apparent, Pinapp, and active input power, Pinact, load power, PI, efficiency and PF at nominal line for 100kΩ load.

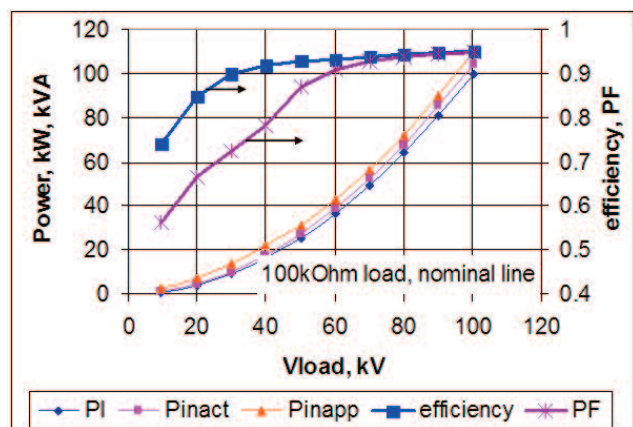


Fig.12. Same as in Figure 11 for 200kΩ load.

ARTICLES

**Highly Efficient Switch-Mode 100kV, 100kW
Power Supply for ESP Applications****ACKNOWLEDGMENTS**

The authors thank their colleagues at Spellman for massive support of this work, and especially Mr. A. Lipovich for his contribution to the mechanical design, and Mr. A. Silverberg for the realization of the phase-shift algorithm.

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ARTICLES

**High Power, High Efficiency, Low Cost Capacitor Charger
 Concept and Demonstration**
**High Power, High Efficiency, Low Cost
 Capacitor Charger Concept and Demonstration**

 Alex Pokryvailo, Costel Carp and Cliff Scapellati
 Spellman High Voltage Electronics Corporation

 Presented at 17th IEEE International Pulsed Power Conference
 June 29-July 2, 2009 Washington DC

ABSTRACT

A 20kJ/s, 10kV, 1kHz repetition-rate technology demonstrator design and testing are described. The goal of the development was combining high performance and versatility with low-cost design and good manufacturability. This goal was met using an energy-dosing converter topology with smart controls adapting the switching frequency in such a way as to ensure zero-current switching for all possible scenarios, keeping maximum duty cycle for high power. The switching is accomplished at a frequency of up to 55kHz employing relatively slow IGBTs with low conduction losses. High efficiency allows all-air cooled design that fits into a 19"x10"x24" rack.

Design guidelines are reviewed. Comprehensive PSpice models accounting for numerous parasitic parameters and mimicking controls for the frequency variation were developed, and simulation results are presented. Together with analytical tools, they predicted a pulse-to-pulse repeatability (PPR) of $\pm 0.15\%$; the measured figures are $\pm 0.4\%$ and $\pm 0.5\%$ for short- and long-term operation, respectively, at peak charging and repetition rate. Repeatability analysis is briefed upon here, and to larger extent, in an accompanying paper. Test methods are described. Typical current and voltage traces and results of thermal runs are presented.

INTRODUCTION

Between numerous capacitor charging applications, a combination of high voltage, high charging rate (tens of kJ/s and higher), high pulse repetition rate (PPR), compactness, high efficiency and good pulse-to-pulse repeatability (PPR) is a serious technological challenge. Putting constraints of low-cost and good manufacturability makes the charger development even more difficult. They restrict use of costly switches, e.g., SiC, exotic cooling schemes and materials, leaving freedom to choose proper circuit topology and control strategy to increase the switching frequency with the purpose of shrinking the size and improving PPR. This paper describes an attempt to satisfy the above contradicting requirements within the constraints of low-cost proven technology.

MAIN SPECIFICATIONS

Input Voltage	400 VAC or 480VAC ^{+10%} _{-14%} , 3Φ 50/60 Hz, frequency $\pm 2\%$
Output Voltage	0÷10 kV
Average Charging Rate	20 kJ/s
PRR	Single shot to 1 kHz
Efficiency	>92 % at full charging rate, >85 % at 30 % of rated power
Power factor	>0.93 at full charging rate >0.85 at 30 % of rated power
Pulse to Pulse repeatability	Better than $\pm 0.5\%$ at 1 kHz, 10 kV, full power; long-term Better than $\pm 0.4\%$ at 1 kHz, 10 kV, full power; short-term Better than $\pm 1\%$ at 1 kHz, 2 kV- 10 kV, short-term.
Insulation	Air, 10 kV and below
Size	10½" (6U)H x 19"W x 24"D rack mount
Weight	90 lb (41 kg)
Cooling	Air

DESIGN

A charger block-diagram is shown in Figure 1. The charger comprises a 3-phase input rectifier with soft start and a smoothing filter, a converter module (CM), an HV divider and control means. Triggered by an external source, the charger charges capacitor Cs that is discharged onto a dummy load via a high-power switch DSw.

CM comprises an inverter INV, HV transformer using popular U100/57/25 ferrites, a rectifier R and control means. The CM's heart is a half-bridge quasi-resonant inverter with energy dosing capacitors (Figure 2) [1]-[3]. Work [2] provides the principle and theory of operation. The benefits of this topology are tight control of the energy transfer and inherent limitation of the short circuit current and voltages across the converter components.

The maximum conversion frequency is 55kHz at low rail voltage. The parasitics of the HV transformer together with capacitors Cdiv form the resonant tank circuit. Standard components and subassemblies field-tested in thousands of Spellman HVPS were used throughout for low cost and reliability.

High Power, High Efficiency, Low Cost Capacitor Charger
Concept and Demonstration

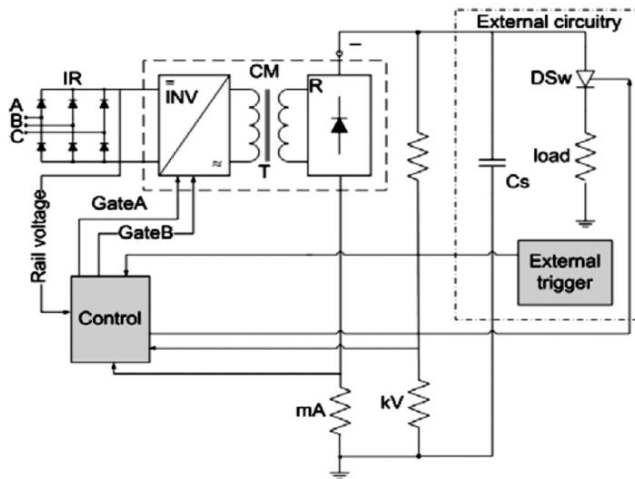


Fig. 1. Charger block-diagram.

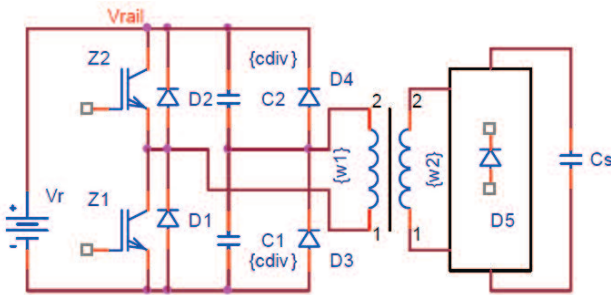


Fig. 2. Halfbridge inverter with energy dosing capacitors.

The FPGA-based controls are characterized by their flexibility ensuing from digital processing capabilities. The standard features include multiple protections (short circuit, overheat, overcurrent and overvoltage, etc.) and means of voltage and current setting. Via firmware, an algorithm is implemented that adapts the switching frequency in such a way as to ensure zero-current switching (ZCS) for all possible scenarios, keeping maximum duty cycle for high power. Thus, the switching losses are virtually non-existent, which allows using relatively slow low-cost switches both on the primary and secondary side.

A precision feedback divider was designed for high-fidelity measurements necessary for good PPR. A risetime of less than 1 μ s and low temperature drift were realized.

The packaging was made in a 19" rack-mounted chassis, 10½" tall, 24" deep. On the front view (Figure 3a), the front panel borrowed from the ubiquitous SR6 series [4] is seen. The filling factor is low as shown in Figure 3b, so the unit, weighing in at 41kg, is relatively light.

Comprehensive PSpice models accounting for numerous parasitic parameters and mimicking controls for the frequency variation were developed assisting in both the

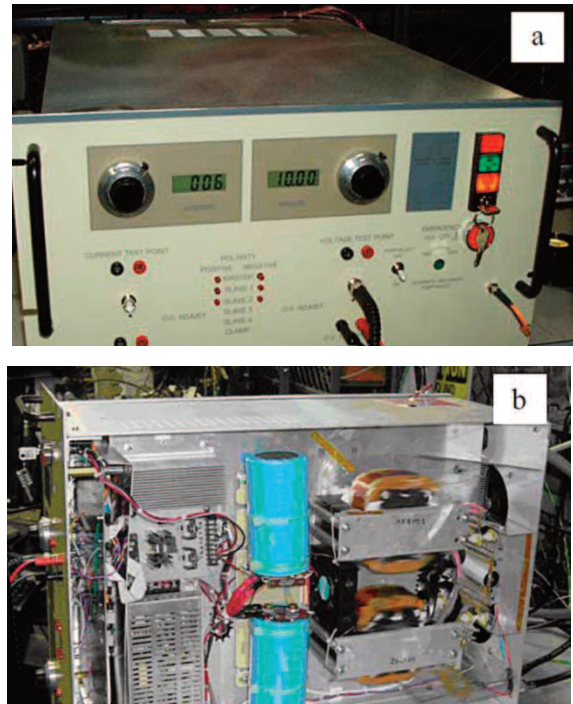


Fig. 3. Charger a – front view; b – HV section.

design and interpretation of the experimental data. A sample of simulated waveforms is given in Figure 4 for the cases of low- and high line voltage. In these simulations, Cs was 200 nF, approximately half of that used in the experiments. It is seen that at any moment (except the first pulse) during the charging cycle ZCS is attained. This was confirmed experimentally.

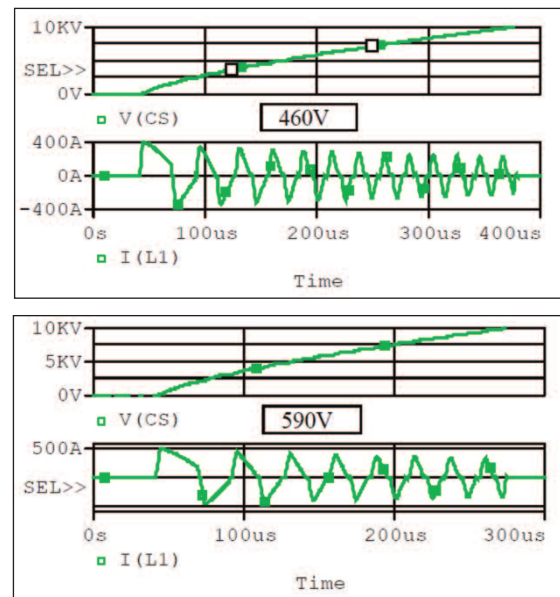


Fig. 4. PSpice simulation for 460V and 590VDC rail voltage.
Cs=200nF.

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 High Power, High Efficiency, Low Cost Capacitor Charger
 Concept and Demonstration

EXPERIMENTAL

Measurement Means

For the measurement of the high-frequency current of the inverter components, Rogowski probes of PEM make, model CWT15, were used. The Cs voltage was measured by a Tektronix P6015A probe. Floating voltage measurements were performed by a differential Tektronix probe P5200. Efficiency and power factor were measured with a Voltech power meter, model PM300.

Waveforms

One of the main goals of this work was realizing as high efficiency as possible by enforcing lossless switching in all possible scenarios at all charge levels and repetition rates. The noise immunity of the control circuitry in this sense is also an important issue. A thorough experimental investigation side by side with PSpice modeling was performed. We found that no under circumstances ZCS was disturbed. Several screens below illustrate the results. Figure 6a shows Vc and primary winding current I1 in burst operation at a PRR of 1400Hz for Cs=420nF (charge rate of 29.4kJ/s), with the collector current, Ic, of one of the transistors displayed on expanded scale in Figure 6b.

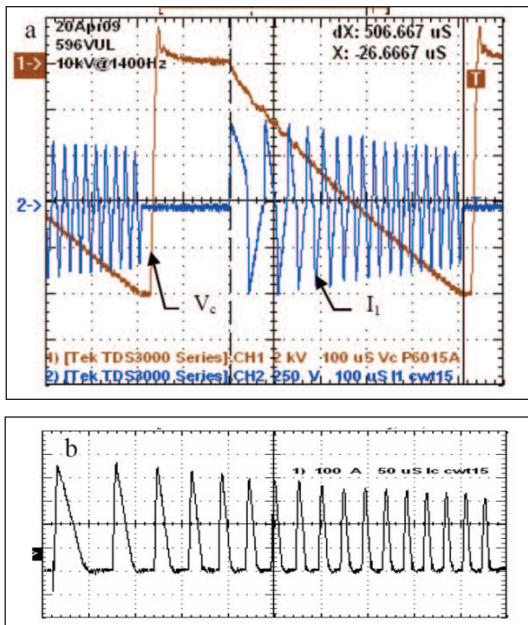


Fig. 5. Typical waveforms at highline. PRR=1400Hz in burst, charge time is 507μs. a – load capacitor voltage and primary winding current; b – collector current.

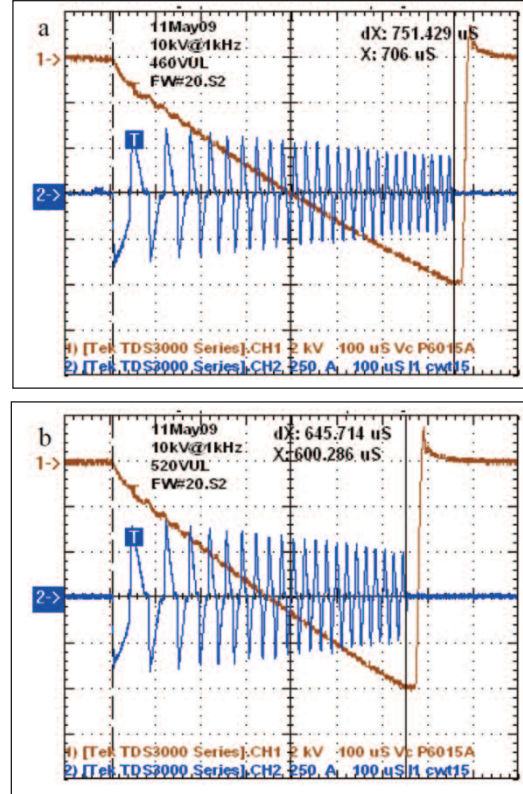


Fig. 6. Typical waveforms at 10 kV@1000 Hz at low (a) and nominal (b) line.

At low line (longest charge), Cs=420nF is charged in 750μs (Figure 6a), so continuous operation with such load is limited to a PRR of 1kHz, if ample dead time is desirable between the shots. At higher line voltage, the charge is accomplished faster (Figure 5a, Figure 6b). As vividly seen in Figure 5b, the conversion frequency adapts to keep high duty cycle yet maintaining ZCS; there are no shoot-through currents. The highest conversion frequency is 55kHz at low line, with very large margin guaranteeing ZCS even at abnormal line sags.

Repeatability

PRR is an important parameter in capacitor charging applications. It influences stability of various physical processes ranging from lasing to pulsed X-rays to plasma chemistry applications. PRR, R, is defined here¹ as

$$R = \frac{V_{Cmax} - V_{Cmin}}{V_{Cavg}}$$

where V_{Cmax}, V_{Cmin} and V_{Cavg} are maximum, minimum and average values of the voltage across the storage cap for a

ARTICLES

**High Power, High Efficiency, Low Cost Capacitor Charger
 Concept and Demonstration**

predefined number of pulses. Pulse-to-pulse variability evolves from several factors:

- 1.) Converter remnant energy, E_{rem} , at the End-of-Charge (EOC). This energy can be stored in the HV transformer magnetic system, its parasitic capacitance, resonant capacitors, buswork, etc. E_{rem} may flow wholly or partially to the storage capacitor, so the output voltage will be higher than the programmed value.
- 2.) Error in generating EOC signal. This may be caused by poor-quality feedback, noise, unstable reference voltage, etc.
- 3.) Delay, t_d , between EOC and actual IGBT turn-off. It comprises digital delays, optocouplers delay, and IGBT turn-off delay. Even constant t_d , if commensurable with half-period, affects PPR. Depending on the circuitry and the components, t_d can be fractions of a microsecond, i.e., t_d is commensurable with half-period.

We will distinguish here between short-term and long-term PPR. The former is defined as that derived from N consecutive pulses. In our measurements, $N=80$, sampled from 121st to the 200th pulse. Thus, short-term PPR is not influenced by thermal drifts, aging of components, etc. It is affected by the rail voltage variations to the extent of the high-frequency rail voltage ringing, excluding slow input changes. Long-term PPR is also influenced by the rail voltage variation in the full defined range, for instance, from 460VDC to 590VDC (corresponding to 400VAC +10%, -14%). In this report, the reference to long-term PPR is made in the light of such variations, other parameters being not controlled.

PPR measurements were taken using the FastFrame capability of a DPO7054 scope. Up to four signals were monitored simultaneously. The load voltage, V_c , was measured again by the P6015A probe, but on a 100mV scale with a 10V offset allowing the signal at end-of-charge (EOC) fit the screen. In addition, the feedback voltage, V_{fdbk} (with the same sensitivity and offset), and primary current were monitored. The shortcoming of these *direct* measurements is their low resolution, of the order of several bits of the scope vertical resolution. Arguably, a better technique is differential measurement, e.g., monitoring the difference between the feedback voltage and the programming voltage. In such a way, at EOC the scope would see virtually zero voltage. In the differential measurement, the feedback voltage was biased with a voltage equal to the programming value. After finding fair matching of the V_c and differential V_{fdbk} data, we continued with direct V_c measurement only.

The scope was triggered by the EOC event. Note that the discharge switch DSw is fired on in 20 μ s after EOC. The first 800 shots were collected with a 500pnt resolution on a 4 μ s/div scale. The waveforms were saved as screen captures, and 80 frames, starting from 121st frame, were saved in the csv format. An Excel spreadsheet was designed, in which 79 shots² were processed; they are graphed in Figure 7 for several rail voltages showing pulse-to-pulse V_c variation.

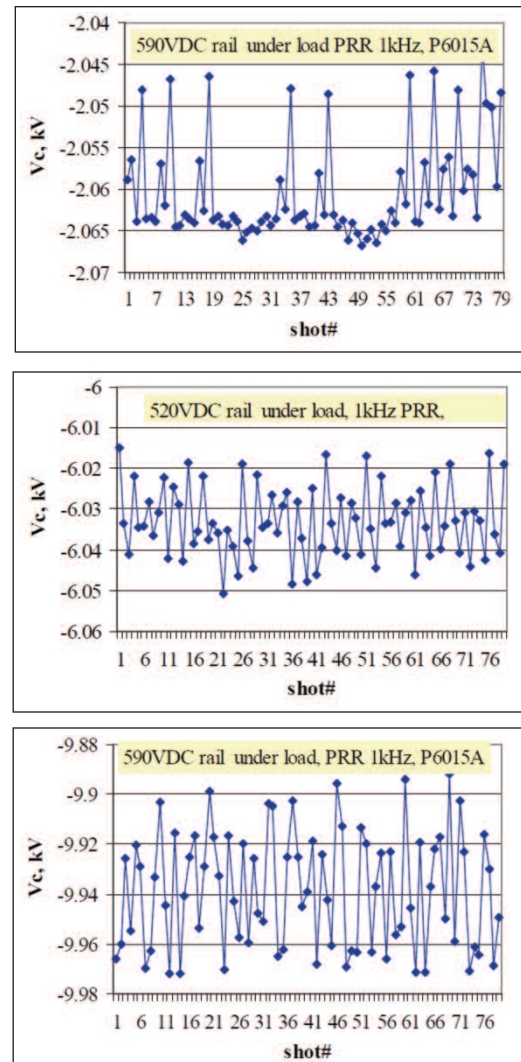


Fig. 7. Shot-to-shot variability taken with FastFrame. Cs=420nF, 1kHz replate, 2kV, 6kV and 10kV settings. See inset annotations for rail voltage.

¹PPR is defined by most vendors as $\pm xx\%$, so 1% in our measurements corresponds to $\pm 0.5\%$ in their definition

²Values shown are averages of 50 points, starting from 250pnt of the acquisition (approximately, the middle part of the screen Figure 8).

ARTICLES

 High Power, High Efficiency, Low Cost Capacitor Charger
 Concept and Demonstration

Three typical screenshots of the overlays of 80 frames are shown in Figure 8. They correspond to data Figure 7 and show quite vividly wherefrom the variability, at least partially, evolves. At EOC, the primary current is chopped at random. If there is a certain pattern (as seen at 2kV and 6kV settings), PPR is better. When the current is chopped at an arbitrary time point (10kV setting), at the rising and trailing edges, and at zero, PPR deteriorates. It still remains below $\pm 0.5\%$ at maximum voltage and PRR, owing to specifics of the used converter topology and high conversion frequency.

For 3 rail voltage settings, namely 460VDC, 520VDC and 590VDC, PPR was calculated by the formula, in Excel convention,

$$\frac{(\min(A2:C80) - \max(A2:C80))}{\text{average}(A2:C80) * 100},$$

where columns A-C contain each V_c values for 79 consecutive pulses, for 460, 520 and 590VDC, respectively. Alternatively, we varied the line voltage continuously from the low to high level, looking for the least stable operation, i.e., for the largest V_c variation. For this method, PPR was calculated by (1) using V_{Cmax} , V_{Cmin} values from the whole measurement range.

Short- and long-term PPR are plotted in Figure 9, Figure 10, respectively. The experimental curves shown in Figure 10 are calculated by (1), (2); they are marked as “3 rail experimental” and “overall experimental cont rails”, respectively. The variability is larger than predicted by theory accounting for the Factor 1 only (“analytical” curve—see accompanying paper). This discrepancy can be attributed to the measurement errors and propagation delays (Factors 2, 3).

With much smaller $C_s=33\text{nF}$ the charge to 10kV is accomplished in $53\mu\text{s}$ at low line, which allows PRR of 10kHz with short-term- and long-term repeatability of 1.5% and 4.6%, respectively. However, the existing DSw limits the operation to 1kHz CW.

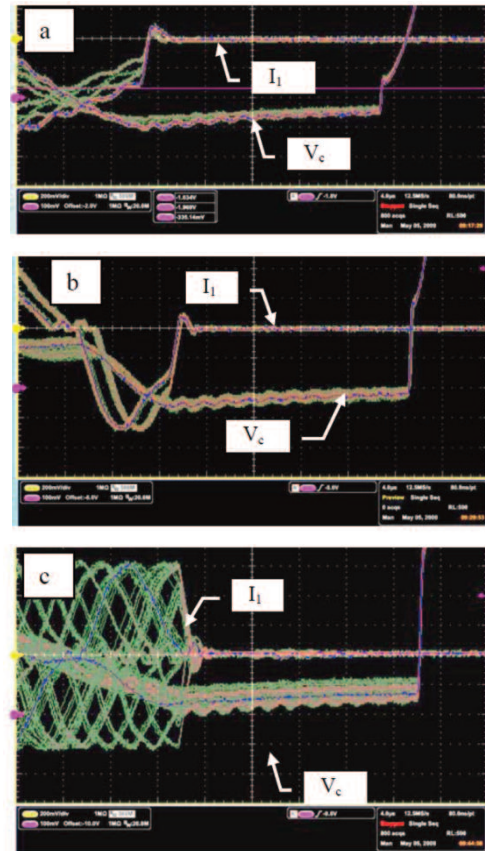


Figure 8. Overlay of 80 frames (V_c - 100 V/div, I_1 - 100 A/div) for:
 a) high line, 2kV@1kHz; b) nominal line, 6kV@1kHz;
 c) high line, 10kV@1kHz

Efficiency and Power Factor

The efficiency is calculated from the values of the input and load power, the former being measured by a Voltech PM300 power meter. Measuring the load power is indirect. It is actually calculated as the energy per shot delivered to the storage capacitor ($E=C_s V_c^2/2$) multiplied by PPR. At full power, the efficiency was about 92%, and power factor, PF, was 94% (Figure 11). The efficiency values are lower by 1-2% than expected and what could be deducted from the loss estimation, and intuitively from the amount of the dissipated heat. We note that the IGBTs baseplate overheat was less than 40°C at all operational modes. One of the possible sources of error is a low-accuracy V_c measurement (the probe P6015A is specified at $\pm 3\%$ DC attenuation, excluding the oscilloscope error). Every percent of voltage measurement error is translated to 2% of the energy measurement error, so the uncertainty of the efficiency measurement is quite pronounced.

ARTICLES

High Power, High Efficiency, Low Cost Capacitor Charger Concept and Demonstration

CONCLUSION

This development was a test case for low-cost general technology of high repetition rate, high voltage, high power, highly efficient capacitor charging. A crossover of 10kV, 20kJ/s, 1kHz PRR specifications was chosen for the demonstration. An energy-dosing converter topology with smart controls optimizing the switching frequency for high efficiency was used. The switching is accomplished at a frequency of up to 55kHz employing relatively slow inexpensive IGBTs. High efficiency allowed a compact all-air cooled design. Excellent pulse-to-pulse repeatability was demonstrated. As usual, the unit is protected against short-circuit, arc, overvoltage, etc.

ACKNOWLEDGEMENT

The authors thank Mr. A. Lipovich for his help in mechanical design.

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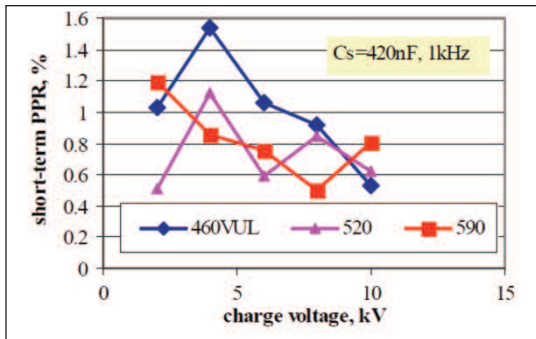


Fig. 9. Short-term repeatability

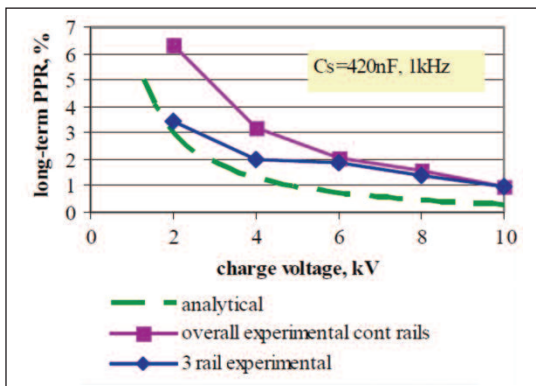


Fig. 10. Long-term repeatability as a function of charge voltage – summary of PSpice and analytical calculations and experimental results.

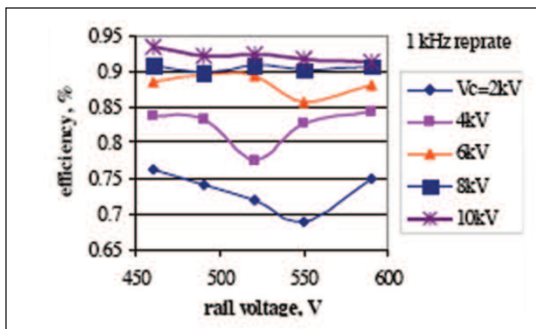


Fig. 11. Efficiency and power factor dependence on rail voltage for several charge voltages.

GLOSSARY

A**ABSOLUTE ACCURACY**

The correctness of the indicated value in terms of its deviation from the true or absolute value.

AC

In text, use lower case: ac. Abbreviation for Alternating Current.

AC BROWNOUT

The condition that exists when the ac line voltage drops below some specified value.

AC LINE

The set of conductors that route ac voltage from one point to another.

AC LINE FILTER

A circuit filter placed in the ac line to condition or smooth out variations that are higher in frequency than the line frequency.

ALTERNATING CURRENT

(ac) A periodic current the average value of which over a period is zero. Unless distinctly specified otherwise, the term refers to a current which reverses at regularly recurring intervals of time and which has alternately positive and negative values.

AMBIENT TEMPERATURE

The average temperature of the environment immediately surrounding the power supply. For forced air-cooled units, the ambient temperature is measured at the air intake. See also Operating Temperature, Storage Temperature, Temperature Coefficient.

AMPERE

(A) Electron or current flow representing the flow of one coulomb per second past a given point in a circuit.

AMPLIFIER

A circuit or element that provides gain.

AMPLIFIER, DC

A direct coupled amplifier that can provide gain for zero-frequency signals.

AMPLIFIER, DIFFERENTIAL

An amplifier which has available both an inverting and a noninverting input, and which amplifies the difference between the two inputs.

AMPLIFIER, INVERTING

An amplifier whose output is 180° out of phase with its input. Such an amplifier can be used with degenerative feedback for stabilization purposes

AMPLIFIER, NONINVERTING

An amplifier whose output is in phase with its input.

AMPLIFIER, OPERATIONAL

A dc amplifier whose gain is sufficiently large that its characteristics and behavior are substantially determined by its input and feedback elements. Operational amplifiers are widely used for signal processing and computational work.

ANODE

1) (electron tube or valve) An electrode through which a principal stream of electrons leaves the interelectrode space. 2) (semiconductor rectifier diode) The electrode from which the forward current flows within the cell. (IEEE Std 100-1988)

ANSI

Abbreviation for American National Standards Institute

APPARENT POWER

Power value obtained in an ac circuit as the product of current times voltage.

ARC

A discharge of electricity through a gas, normally characterized by a voltage drop in the immediate vicinity of the cathode approximately equal to the ionization potential of the gas. (IEE Std 100-1988)

ASYMMETRICAL WAVEFORM

A current or voltage waveform that has unequal excursions above and below the horizontal axis.

ATTENUATION

Decrease in amplitude or intensity of a signal.

AUTHORIZED PERSON

A qualified person who, by nature of his duties or occupation, is obliged to approach or handle electrical equipment or, a person who, having been warned of the hazards involved, has been instructed or authorized to do so by someone in authority.

GLOSSARY

AUTO TRANSFORMER

A single winding transformer with one or more taps.

AUTOMATIC CROSSOVER

The characteristic of a power supply having the capability of switching its operating mode automatically as a function of load or setting from the stabilization of voltage to the stabilization of current. The term automatic crossover power supply is reserved for those units having substantially equal stabilization for both voltage and current. Not used for voltage-limited current stabilizers or current-limited voltage stabilizers. See also CROSSOVER POINT.

AUTOMATIC GAIN CONTROL (AGC)

A process or means by which gain is automatically adjusted in a specified manner as a function of input or other specified parameters. (IEEE Std 100-1988)

AUXILIARY SUPPLY

A power source supplying power other than load power as required for the proper functioning of a device.

AWG

Abbreviation for American Wire Gauge.

B

BANDWIDTH

Based on the assumption that a power supply can be modeled as an amplifier, the bandwidth is that frequency at which the voltage gain has fallen off by 3 dB. Bandwidth is an important determinant of transient response and output impedance.

BASEPLATE TEMPERATURE

The temperature at the hottest spot on the mounting platform of the supply.

BEAD

A small ferrite normally used as a high frequency inductor core.

BEAM SUPPLY

Power supply which provides the accelerating energy for the electrons or ions.

BENCH POWER SUPPLY

Power source fitted with output controls, meters, terminals and displays for experimental bench top use in a laboratory.

BIAS SUPPLY

Power source fitted with output controls, meters, terminals and displays for experimental bench top use in a laboratory.

BIFILAR WINDING

Two conductors wound in parallel.

BIPOLAR

Having two poles, polarities or directions.

BIPOLAR PLATE

An electrode construction where positive and negative active materials are on opposite sides of an electronically conductive plate.

BIPOLAR POWER SUPPLY

A special power supply which responds to the sense as well as the magnitude of a control instruction and is able to linearly pass through zero to produce outputs of either positive or negative polarity.

BIT

A binary unit of digital information having a value of "0" or "1". See also Byte.

BLACK BOX

Element in a system specified by its function, or operating characteristics.

BLEED

A low current drain from a power source.

BLEED RESISTOR

A resistor that allows a small current drain on a power source to discharge filter capacitors or to stabilize an output.

BOBBIN

1) A non-conductive material used to support windings.
2) A cylindrical electrode (usually the positive) pressed from a mixture of the active material, a conductive material, such as carbon black, the electrolyte and/or binder with a centrally located conductive rod or other means for a current collector.

BODE PLOT

A plot of gain versus frequency for a control loop. It usually has a second plot of phase versus frequency.

BOOST REGULATOR

One of several basic families of switching power supply topologies. Energy is stored in an inductor during the pulse then released after the pulse.

GLOSSARY

C

BREAKDOWN VOLTAGE

- 1) The voltage level which causes insulation failure.
- 2) The reverse voltage at which a semiconductor device changes its conductance characteristics.

BRIDGE CIRCUIT

Circuit with series parallel groups of components.

BRIDGE CONVERTER

A power conversion circuit with the active elements connected in a bridge configuration.

BRIDGE RECTIFIER

Full-wave rectifier circuit employing two or more rectifiers in a bridge configuration.

BROWNOUT

The condition created during peak usage periods when electric utility companies intentionally reduce their line voltage by approximately 10 to 15 percent to counter excessive demand.

BUCK REGULATOR

The condition created during peak usage periods when electric utility companies intentionally reduce their line voltage by approximately 10 to 15 percent to counter excessive demand.

BUFFER

An isolating circuit used to prevent a driven circuit from influencing a driving circuit. (IEEE Std 100-1988)

BUFFER

The energy storage capacitor at the front end of a regulator.

BULK VOLTAGE

The energy storage capacitor at the front end of a regulator.

BURN IN

The operation of a newly fabricated device or system prior to application with the intent to stabilize the device, detect defects, and expose infant mortality.

BUS

The common primary conductor of power from a power source to two or more separate circuits.

BYTE

A sequence of binary digits, frequently comprised of eight (8) bits, addressed as a unit. Also see BIT.

CAPACITANCE

Inherent property of an electric circuit or device that opposes change in voltage. Property of circuit whereby energy may be stored in an electrostatic field.

CAPACITANCE-DISTRIBUTED

The capacitance in a circuit resulting from adjacent turns on coils, parallel leads and connections.

CAPACITIVE COUPLING

Coupling resulting from the capacitive effect between circuit elements.

CAPACITANCE, DISTRIBUTED

The current flow between segregated conductive metal parts; voltage and frequency dependent.

CAPACITOR

A device that stores a charge. A simple capacitor consists of two conductors separated by a dielectric. A device that stores a charge. A simple capacitor consists of two conductors separated by a dielectric.

CAPACITOR INPUT FILTER

Filter employing capacitor as its input.

CATHODE

1) (electron tube or valve) An electrode through which a primary stream of electrons enters the interelectrode space. 2) (semiconductor rectifier diode) The electrode to which the forward current flows within the cell. (IEEE Std 100-1988).

CATHODE RAY TUBE (CRT)

A display device in which controlled electron beams are used to present alphanumeric or graphical data on an electroluminescent screen. (IEEE Std 100-1988).

CATHODE RAY TUBE

An electron-beam tube in which the beam can be focused to a small cross section on a luminescent screen and varied in position and intensity to produce a visible pattern. (IEEE Std 100-1988).

CENTER TAP

Connection made to center of an electronic device.

CGS UNIT

Abbreviation for the Centimeter-Gram Second Unit of measurement.

GLOSSARY

CHARGE

1) The conversion of electrical energy, provided in the form of a current from an external source, into chemical energy within a cell or battery. 2) The potential energy stored in a capacitive electrical device.

CHASSIS

The structure supporting or enclosing the power supply.

CHASSIS GROUND

The voltage potential of the chassis.

CHOKE COIL

An inductor.

CHOKE, RF

A choke coil with a high impedance at radio frequencies.

CIRCUIT INPUT FILTER

A filter employing an inductor (L) or an inductor/capacitor (L/C) as its input.

CIRCULAR MIL

Cross-sectional area of a conductor one mil in diameter.

CIRCULATING CURRENT

See GROUND LOOP.

CLAMP DIODE

A diode in either a clipper or clamp circuit.

CLIPPER CIRCUIT

A circuit that blocks or removes the portion of a voltage waveform above some threshold voltage.

CLOSED LOOP CONTROL

A type of automatic control in which control actions are based on signals fed back from the controlled equipment or system. (IEEE Std 100-1988)

CLOSED-LOOP CONTROL SYSTEM

(control system feedback) A control system in which the controlled quantity is measured and compared with a standard representing the desired performance.

Note: Any deviation from the standard is fed back into the control system in such a sense that it will reduce the deviation of the controlled quantity from the standard. (IEEE Std 100-1988)

COLLECTOR

1) Electronic connection between the electrochemical cell electrode and the external circuit. 2) In a transistor, the semiconductor section which collects the majority carriers.

COMMON CHOKE

See INTEGRATED MAGNETICS.

COMMON-MODE NOISE

The component of noise voltage that appears equally and in phase on conductors relative to a common reference.

COMMON-MODE OUTPUT

That electrical output supplied to an impedance connected between the terminals of the ungrounded floating output of a power supply, amplifier, or line-operated device, and the ground point to which the source power is returned.

COMMON POINT

With respect to operationally programmable power supplies one output/sense terminal is designated "common" to which load, reference and external programming signal all return.

COMMON RETURN

A return conductor common to two or more circuits.

COMPARISON AMPLIFIER

A dc amplifier which compares one signal to a stable reference, and amplifies the difference to regulate the power supply power-control elements.

COMPENSATION

The addition of circuit elements to assist in stabilization of a control loop.

COMPLIMENTARY TRACKING

A system of interconnection of two voltage stabilizers by which one voltage (the slave) tracks the other (the master).

COMPLIANCE

Agency certification that a product meets its standards. See also SAFETY COMPLIANCE.

COMPLIANCE VOLTAGE

The output dc voltage of a constant current supply.

COMPLIANCE RANGE

Range of voltage needed to sustain a given constant current throughout a range of load resistance.

CONDUCTANCE (G)

The ability to conduct current. It is equal to amperes per volt, or the reciprocal of resistance, and is measured in siemens (metric) or mhos (English). $G = 1/R$.

GLOSSARY

CONSTANT CURRENT LIMITING CIRCUIT

Current-limiting circuit that holds output current at some maximum value whenever an overload of any magnitude is experienced.

CONSTANT VOLTAGE CHARGE

A charge during which the voltage across the battery terminals is maintained at a steady state.

CONTINUOUS DUTY

A requirement of service that demands operation at a substantially constant load for an indefinitely long time. See also INTERMITTENT DUTY.

CONTROL GRID

A grid, ordinarily placed between the cathode and an anode, for use as a control electrode. (IEEE Std 100-1988)

CONTROL LOOP

A feedback circuit used to control an output signal. See also LOOP.

CONTROL RANGE

The parameter over which the controlled signal maybe adjusted and still meet the unit specifications.

CONTROL REMOTE

Control over the stabilized output signal by means located outside or away from the power supply. May or may not be calibrated.

CONTROL RESOLUTION

The smallest increment of the stabilized output signal that can be reliably repeated.

CONVECTION-COOLED POWER SUPPLY

A power supply cooled exclusively from the natural motion of a gas or a liquid over the surfaces of heat dissipating elements.

CONVERTER

A device that changes the value of a signal or quantity. Examples: DC-DC; a device that delivers dc power when energized from a dc source. Fly-Back; a type of switching power supply circuit. See also FLYBACK CONVERTER. Forward; a type of switching power supply circuit. See also FORWARD CONVERTER.

CORE

Magnetic material serving as a path for magnetic flux.

CORONA

1) (air) A luminous discharge due to ionization of the air surrounding a conductor caused by a voltage gradient exceeding a certain critical value. 2) (gas) A discharge with slight luminosity produced in the neighborhood of a conductor, without greatly heating it, and limited to the region surrounding the conductor in which the electric field exceeds a certain value. 3) (partial discharge) (corona measurement) A type of localized discharge resulting from transient gaseous ionization in an insulation system when the voltage stress exceeds a critical value. The ionization is usually localized over a portion of the distance between the electrodes of the system. (IEEE Std 100-1988)

CORONA EXTINCTION VOLTAGE

(CEV) (corona measurement) The highest voltage at which continuous corona of specified pulse amplitude no longer occurs as the applied voltage is gradually decreased from above the corona inception value. Where the applied voltage is sinusoidal, the CEV is expressed as 0.707 of the peak voltage. (IEEE Std 100-1988)

CORONA INCEPTION VOLTAGE

(CIV) (corona measurement) The lowest voltage at which continuous corona of specified pulse amplitude occurs as the applied voltage is gradually increased. Where the applied voltage is sinusoidal, the CIV is expressed as 0.707 of the peak voltage. (IEEE Std 100-1988)

CREEPAGE

The movement of electrolyte onto surfaces of electrodes or other components of a cell with which it is not normally in contact.

CREEPAGE DISTANCE

The shortest distance separating two conductors as measured along a surface touching both conductors.

CROSS-REGULATION

In a multiple output power supply, the percent voltage change at one output caused by the load change on another output.

CROSSOVER POINT

That point on the operating locus of a voltage/current automatic crossover power supply formed by the intersection of the voltage-stabilized and current-stabilized output lines. The resistance value (E/I) defined by this intersection is the matching impedance of the power supply, which will draw the maximum output power. See also AUTOMATIC CROSSOVER.

GLOSSARY

CROSSOVER, VOLTAGE/CURRENT

Voltage/Current crossover is that characteristic of a power supply that automatically converts the mode of operation from voltage regulation to current regulation (or vice versa) as required by preset limits.

CROWBAR

An overvoltage protection circuit which rapidly places a low resistance shunt across the power supply output terminals if a predetermined voltage is exceeded.

CSA

Abbreviation for Canadian Standards Association.

CURRENT CONTROL

See CURRENT STABILIZATION

CURRENT FOLDBACK

See FOLDBACK CURRENT LIMITING.

CURRENT LIMIT KNEE

The point on the plot of current vs voltage of a supply at which current starts to foldback, or limit.

CURRENT LIMITING

An electronic overload protection circuit which limits the maximum output current to a preset value.

CURRENT MODE

The functioning of a power supply so as to produce a stabilized output current.

CURRENT SENSING RESISTOR

A resistor placed in series with the load to develop a voltage proportional to load current.

CURRENT SOURCE

A power source that tends to deliver constant current.

CURRENT STABILIZATION

The process of controlling an output current.

D

DC

In text, use lower case: dc. Abbreviation for Direct Current.

DC COMPONENT

The dc value of an ac wave that has an axis other than zero.

DC-DC CONVERTER

A circuit or device that changes a dc input signal value to a different dc output signal value.

DECAY TIME

See FALL TIME

DERATING

(reliability) The intentional reduction of stress/strength ratio in the application of an item, usually for the purpose of reducing the occurrence of stress-related failures. (IEEE Std 100-1988)

DIELECTRIC

An insulating material between conductors.

DIELECTRIC CONSTANT (K)

For a given dielectric material, the ratio of the value of a capacitor using that material to the value of an equivalent capacitor using a standard dielectric such as dry air or a vacuum.

DIELECTRIC WITHSTAND VOLTAGE

Voltage an insulating material will withstand before flashover or puncture.

See also HI-POT TEST, ISOLATION.

DIFFERENTIAL VOLTAGE

The difference in voltages at two points as measured with respect to a common reference.

DRIFT

A change in output over a period of time independent of input, environment or load

DRIVER

A current amplifier used for control of another device or circuit.

DUTY CYCLE

1) The ratio of time on to time off in a recurring event. 2) The operating regime of a cell or battery including factors such as charge and discharge rates, depth of discharge, cycle length and length of time in the standby mode.

DYNAMIC FOCUS

A means of modulating the focus voltage as a function of the beam position. (Bertan High Voltage)

DYNAMIC LOAD

A load that rapidly changes from one level to another. To be properly specified, both the total change and the rate of change must be stated.

GLOSSARY

E**EARTH**

An electrical connection to the earth frequently using a grid or rod(s). See also GROUND.

E-BEAM

Electron Beam. (Bertan High Voltage)

EDDY CURRENTS

A circulating current induced in a conducting material by a varying magnetic field.

EFFECTIVE VALUE

The value of a waveform that has the equivalent heating effect of a direct current. For sine waves, the value is .707 X Peak Value; for non-sinusoidal waveforms, the Effective Value = RMS (Root Mean Square) Value.

EFFICIENCY

- 1) The ratio of total output power to total input power, expressed as a percentage, under specified conditions.
- 2) The ratio of the output of a secondary cell or battery on discharge to the input required to restore it to the initial state of charge under specified conditions.

ELECTRIC

Containing, producing, arising from, actuated by, or carrying electricity, or designed to carry electricity and capable of so doing. Examples: Electric eel, energy, motor, vehicle, wave. Note: Some dictionaries indicate electric and electrical as synonymous, but usage in the electrical engineering field has in general been restricted to the meaning given in the definitions above. It is recognized that there are borderline cases wherein the usage determines the selection. See ELECTRICAL. (IEEE Std 100-1988)

ELECTRICAL

(general) Related to, pertaining to, or associated with electricity but not having its properties or characteristics. Examples: Electrical engineer, handbook, insulator, rating, school, unit.

ELECTRON BEAM

A collection of electrons which may be parallel, convergent, or divergent. (Bertan High Voltage)

ELECTRON (e-)

Negatively charged particle.

ELECTRON GUN

(electron tube) An electrode structure that produces and may control, focus, deflect, and converge one or more electron beams. (IEEE Std 100-1988)

ELECTRONIC

Of, or pertaining to, devices, circuits, or systems utilizing electron devices. Examples: Electronic control, electronic equipment, electronic instrument, and electronic circuit. (IEEE Std 100-1988)

ELECTRONIC LOAD

A test instrument designed to draw various and specified amounts of current or power from a power source.

ELECTRON VOLT

A measure of energy. The energy acquired by an electron passing through a potential of one volt.

ELECTROPHORESIS

A movement of colloidal ions as a result of the application of an electric potential. (IEEE Std 100-1988)

EMF

Abbreviation for Electromotive Force.

EMI

Abbreviation for Electromagnetic Interference.

EMI FILTER

A circuit composed of reactive and resistive components for the attenuation of radio frequency components being emitted from a power supply. See also EMI.

EMI FILTERING

Process or network of circuit elements to reduce electromagnetic interference emitted from or received by an electronic device. See also EMI.

EMISSION

1) (laser-maser) The transfer energy from matter to a radiation field. 2) (radio-noise emission) An act of throwing out or giving off, generally used here in reference to electromagnetic energy. (IEEE Std 100-1988)

EMISSION CURRENT

The current resulting from electron emission. (IEEE Std 100-1988)

EQUIVALENT CIRCUIT

An electrical circuit that models the fundamental properties of a device or circuit.

EQUIVALENT LOAD

An electrical circuit that models the fundamental properties of a load.

GLOSSARY

EQUIVALENT SERIES INDUCTANCE (ESI)

The amount of inductance in series with an ideal capacitor which exactly duplicates the performance of a real capacitor.

EQUIVALENT SERIES RESISTANCE (ESR)

The amount of resistance in series with an ideal capacitor which exactly duplicates the performance of a real capacitor.

ERROR AMPLIFIER

An operational amplifier, or differential amplifier, in a control loop that produces an error signal whenever a sensed output differs from a reference voltage.

ERROR SIGNAL

The output voltage of an error amplifier produced by the difference between the reference and the input signal times the gain of the amplifier.

ERROR VOLTAGE

The output voltage of the error amplifier in a control loop.

ESD

Abbreviation for Electrostatic Discharge.

ESL

Abbreviation for Equivalent Series Inductance.

ESR

Abbreviation for Equivalent Series Resistance.

F

FAILURE MODE

The way in which a device has ceased to meet specified minimum requirements.

FALL TIME

The time required for a pulse to decrease from 90 percent to 10 percent of its maximum positive (negative) amplitude.

FAN COOLED

A method of forced-air cooling used to maintain design.

FARAD

Unit of measurement of capacitance. A capacitor has a capacitance of one farad when a charge of one coulomb raises its potential one volt: $C = Q/E$.

FEEDBACK

The process of returning part of the output signal of a system to its input.

FEED FORWARD

A control technique whereby the line regulation of a power supply is improved by directly sensing the input voltage.

FEED THROUGH

A plated-through hole in a printed circuit board which electrically connects a trace on top of the board with a trace on the bottom side.

FERRITE

A ceramic material that exhibits low loss at high frequencies, and which contains iron oxide mixed with oxides or carbonates of one or more metals such as manganese, zinc, nickel or magnesium.

FET

Abbreviation for Field Effect Transistor.

FIELD EFFECT TRANSISTOR (FET)

Transistor in which the resistance of the current path from source to drain is modulated by applying a transverse electric field between two electrodes. See also JUNCTION FIELD EFFECT TRANSISTOR, METAL OXIDE, SEMICONDUCTOR FIELD EFFECT TRANSISTOR.

FIELD EMISSION

Electron emission from a surface due directly to high voltage gradients at the emitting surface. (IEEE Std 100-1988)

FIELD EMISSION GUN

An electron gun with an extractor electrode which pulls or extracts electrons off the filament.

FILAMENT

(electron tube) A hot cathode, usually in the form of a wire or ribbon, to which heat may be supplied by passing current through it. Note: This is also known as a filamentary cathode. (IEEE Std 100-1988)

FILAMENT CURRENT

The current supplied to a filament to heat it. (IEEE Std 100-1984)

FILAMENT OUTPUT

Power supply which heats the filament of an electron column, CRT or x-ray tube. In some applications, the filament output "floats" on the accelerating voltage. (Bertan High Voltage)

GLOSSARY

FILAMENT VOLTAGE

Power supply which heats the filament of an electron column, CRT or x-ray tube. In some applications, the filament output "floats" on the accelerating voltage. (Bertan High Voltage)

FILTER

One or more discrete components positioned in a circuit to attenuate signal energy in a specified band of frequencies.

FLASHOVER

1) (general) A disruptive discharge through air around or over the surface of solid or liquid insulation, between parts of different potential or polarity, produced by the application of voltage wherein the breakdown path becomes sufficiently ionized to maintain an electric arc. 2) (high voltage ac cable termination) A disruptive discharge around or over the surface of an insulating member, between parts of different potential or polarity, produced by the application of voltage wherein the breakdown path becomes sufficiently ionized to maintain an electric arc. 3) (high voltage testing) Term used when a disruptive discharge occurs over the surface of a solid dielectric in a gaseous or liquid medium. (IEEE Std 100-1988)

FLOATING NETWORK OR COMPONENTS

A network or component having no terminal at ground potential. (IEEE Std 100-1988)

FLOATING OUTPUT

Ungrounded output of a power supply where either output terminal may be referenced to another specified voltage.

FLYBACK CONVERTER

A power supply switching circuit which normally uses a single transistor. During the first half of the switching cycle the transistor is on and energy is stored in a transformer primary; during the second half of the switching cycle this energy is transferred to the transformer secondary and the load.

FOCUS

(oscilloscope) Maximum convergence of the electron beam manifested by minimum spot size on the phosphor screen. (IEEE Std 100-1988)

FOCUSING ELECTRODE

(beam tube) An electrode the potential of which is adjusted to focus an electron beam. (IEEE Std 100-1988)

FOLDBACK CURRENT LIMITING

A power supply output protection circuit whereby the output current decreases with increasing overload, reaching a minimum at short circuit. This minimizes the internal power dissipation under overload conditions. Foldback current limiting is normally used with linear regulators

FORWARD CONVERTER

A power supply switching circuit that transfers energy to the transformer secondary when the switching transistor is on.

FREE WHEEL DIODE

A diode in a pulse-width modulated switching power supply that provides a conduction path for the counter electromotive force of an output choke.

FREQUENCY

Number of cycles per second (measured in Hertz).

FULL BRIDGE CONVERTER

A power switching circuit in which four power switching devices are connected in a bridge configuration to drive a transformer primary.

FULL BRIDGE RECTIFIER

A rectifier circuit that employs four diodes per phase.

FULL WAVE RECTIFIER

Rectifier circuit that produces a dc output for each half cycle of applied alternating current.

FUSE

Safety protective device that permanently opens an electric circuit when overloaded. See also OVERCURRENT DEVICE, OVERCURRENT PROTECTIVE DEVICE.

G

GAIN

Ratio of an output signal to an input signal. See also CLOSED LOOP GAIN, GAIN MARGIN, OPEN LOOP GAIN.

GAUSS

Measure of flux density in Maxwells per square centimeter of cross-sectional area. One Gauss is 10⁻⁴ Tesla

GLITCH

1) An undesired transient voltage spike occurring on a signal. 2) A minor technical problem arising in electrical equipment.

GLOSSARY

GPIB

General purpose interface bus, also known as IEEE-488. (Bertan High Voltage)

GRID

1) In batteries, a framework for a plate or electrode which supports or retains the active materials and acts as a current collector. 2) In vacuum tubes, an element used to control the flow of electrons. 3) A network of equally spaced parallel lines, one set spaced perpendicular to the other.

GROUND

A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to earth, or to some conducting body that serves in place of earth. (National Electric Code)

GROUND BUS

A bus to which individual grounds in a system are attached and that in turn is grounded at one or more points.

GROUNDING

Connected to or in contact with earth or connected to some extended conductive body which serves instead of the earth.

GROUND LOOP

A condition that causes undesirable voltage levels when two or more circuits share a common electrical return or ground lines.

H

HALF-BRIDGE CONVERTER

A switching power supply design in which two power switching devices are used to drive the transformer primary. See also BRIDGE RECTIFIER.

HALF-WAVE RECTIFIER

A circuit element, such as a diode, that rectifies only one-half the input ac wave to produce a pulsating dc output.

HEADROOM

The difference between the bulk voltage and the output voltage in a linear series pass regulator. See also DIFFERENTIAL VOLTAGE.

HEAT SINK

The medium through which thermal energy is dissipated.

HENRY (H)

Unit of measurement of inductance. A coil has one henry of inductance if an EMF of one volt is induced when current through an inductor is changing at rate of one ampere per second

HERTZ (Hz)

The SI unit of measurement for frequency, named in honor of Heinrich Hertz who discovered radio waves. One hertz equals one cycle per second.

HICCUP

A transient condition that momentarily confuses a control loop.

HIGH LINE

Highest specified input operating voltage.

HIGH VOLTAGE ASSEMBLY

The portion of a high voltage power supply which contains the high voltage circuits which are critical to the performance and reliability of a high voltage power supply. (Bertan High Voltage)

HI-POT TEST (HIGH POTENTIAL TEST)

A test performed by applying a high voltage for a specified time to two isolated points in a device to determine adequacy of insulating materials.

HOLDING TIME

See HOLDUP TIME

HOLDUP TIME

The time under worst case conditions during which a power supply's output voltage remains within specified limits following the loss or removal of input power. Sometimes called Holding Time or Ride-Through.

HYBRID SUPPLIES

A power supply that combines two or more different regulation techniques, such as ferroresonant and linear or switching and linear, or one that takes advantage of hybrid technology.

I

I-BEAM

Ion Beam. (Bertan High Voltage)

IC

Abbreviation for Integrated Circuit.

GLOSSARY

IEC

Abbreviation for International Electrotechnical Commission.

IEEE

Abbreviation for Institute of Electrical and Electronics Engineers.

IMPEDANCE (Z)

Total resistance to flow of an alternating current as a result of resistance and reactance.

INDUCED CURRENT

Current that flows as a result of an Induced EMF (Electromotive Force).

INDUCED EMF

Voltage induced in a conductor in a varying magnetic field.

INPUT

The ability to turn off the output of a power supply from a remote location

INDUCED IMPEDANCE

The impedance of the input terminals of a circuit or device, with the input disconnected.

INDUCED FILTER

A low-pass or band-reject filter at the input of a power supply which reduces line noise fed to the supply. This filter may be external to the power supply.

INDUCED SURGE

See INRUSH CURRENT

INPUT VOLTAGE RANGE

The range of input voltage values for which a power supply or device operates within specified limits.

INRUSH CURRENT

The range of input voltage values for which a power supply or device operates within specified limits.

INSTANTANEOUS VALUE

The measured value of a signal at a given moment in time.

INSULATION

Non-conductive materials used to separate electric circuits.

INSULATION RESISTANCE

The resistance offered, usually measured in megohms, by an insulating material to the flow of current resulting from an impressed dc voltage

INVERTER

1) A device that changes dc power to ac power. 2) A circuit, circuit element or device that inverts the input signal.

ION BEAM

A collection of ions which may be parallel, convergent, or divergent. (Bertan High Voltage)

ION GUN

A device similar to an electron gun but in which the charged particles are ions. Example: proton gun. (IEEE Std 100-1988)

ISOLATION

The electrical separation between two circuits, or circuit elements.

ISOLATION TRANSFORMER

A transformer with a one-to-one turns ratio. See also STEP-DOWN TRANSFORMER STEP-UP TRANSFORMER, TRANSFORMER

ISOLATION VOLTAGE

The maximum ac or dc specified voltage that may be continuously applied between isolated circuits.

J

JOULE (J)

Unit of energy equal to one watt-second.

K

KELVIN (K)

1) Unit of temperature in the International System of Units (SI) equal to the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The kelvin temperature scale uses Celsius degrees with the scale shifted by 273.16. Therefore, 0 K is at absolute zero. Add 273.16 to any Celsius value to obtain the corresponding value in kelvins. 2) A technique using 4 terminals to isolate current carrying leads from voltage measuring leads.

KIRCHOFF'S CURRENT LAW

At any junction of conductors in a circuit, the algebraic sum of the current is zero

KIRCHOFF'S VOLTAGE LAW

In a circuit, the algebraic sum of voltages around the circuit is equal to zero.

GLOSSARY

L

LATCH-UP

A part of the control circuit for a power supply that goes into a latched condition.

L-C FILTER

A low pass filter that consists of an inductance (L) and a capacitance (C). Also known as an averaging filter.

LEAKAGE CURRENT

- 1) The ac or dc current flowing from input to output and/or chassis of an isolated device at a specified voltage.
- 2) The reverse current in semiconductor junctions.

LED

Symbol for Light-Emitting Diode.

LINE

- 1) Medium for transmission of electricity between circuits or devices.
- 2) The voltage across a power transmission line. See also HIGH LINE, LOW LINE.

LINEAR

- 1) In a straight line.
- 2) A mathematical relationship in which quantities vary in direct proportion to one another, the result of which, when plotted, forms a straight line.

LINEARITY

- 1) The ideal property wherein the change in the value of one quantity is directly proportional to the change in the value of another quantity, the result of which, when plotted on graph, forms a straight line.
- 2) Commonly used in reference to Linearity Error.

LINEAR SUPPLY REGULATION

The deviation of the output quantity from a specified reference line.

LINEAR PASS

See SERIES PASS

LINEAR REGULATION

A regulation technique wherein the control device, such as transistor, is placed in series or parallel with the load. Output is regulated by varying the effective resistance of the control device to dissipate unused power. See also LINEAR SUPPLY, REGULATION.

LINEAR REGULATOR

A power transformer or a device connected in series with the load of a constant voltage power supply in such a way that the feedback to the series regulator changes its voltage drop as required to maintain a constant dc output.

LINEAR SUPPLY REGULATION

An electronic power supply employing linear regulation techniques. See also LINEAR REGULATION.

LINE CONDITIONER

A circuit or device designed to improve the quality of an ac line.

LINE EFFECT

See LINE REGULATION.

LINE REGULATION

A regulation technique wherein the control device, such as transistor, is placed in series or parallel with the load. Output is regulated by varying the effective resistance of the control device to dissipate unused power. See also LINEAR SUPPLY, REGULATION.

LINE REGULATOR

Power conversion equipment that regulates and/or changes the voltage of incoming power.

LINE TRANSIENT

A perturbation outside the specified operating range of an input or supply voltage.

LOAD

Capacitance, resistance, inductance or any combination thereof, which, when connected across a circuit determines current flow and power used.

LOAD DECOUPLING

The practice of placing filter components at the load to attenuate noise.

LOAD EFFECTS

See LOAD REGULATION

LOAD IMPEDANCE

The complex resistance to the flow of current posed by a load that exhibits both the reactive and resistive characteristics.

LOAD REGULATION

- 1) Static: The change in output voltage as the load is changed from specified minimum to maximum and maximum to minimum, with all other factors held constant.
- 2) Dynamic: The change in output voltage expressed as a percent for a given step change in load current. Initial and final current values and the rates of change must be specified. The rate of change shall be expressed as current/unit of time, e.g., 20 amperes A/ μ second. The dynamic regulation is expressed as a $\pm$ percent for a worst case peak-to-peak deviation for dc supplies, and worst case rms deviation for ac supplies.

GLOSSARY

LOCAL CONTROL

Control over the stabilized output signal by means located within or on the power supply. May or may not be calibrated.

LOCAL SENSING

Using the power supply output voltage terminals as the error-sensing points to provide feedback to the voltage regulator.

LOGIC HIGH

A voltage representing a logic value of one (1) in positive logic.

LOGIC INHIBIT/ENABLE

A referenced or isolated logic signal that turns a power supply output off or on.

LOGIC LOW

A voltage representing a logic value of zero (0) in positive logic.

LONG-TERM STABILITY

The output voltage change of a power supply, in percent, due to time only, with all other factors held constant. Long-term stability is a function of component aging.

LOOP

The path used to circulate a signal. See also CLOSED LOOP, CONTROL LOOP, OPEN LOOP.

LOOP GAIN

The ratio of the values of a given signal from one point to another in a loop. See also GAIN.

LOOP RESPONSE

The speed with which a loop corrects for specified changes in line or load.

LOOP STABILITY

A term referencing the stability of a loop as measured against some criteria, e.g., phase margin and gain margin.

LOW LINE

Lowest specified input operating voltage.

M

MAINS

The utility AC power source.

MASTER-SLAVE OPERATION

A method of interconnecting two or more supplies such that one of them (the master) serves to control the others (the slaves). The outputs of the slave supplies always remain equal to or proportional to the output of the master

MAXIMUM LOAD

1) The highest allowable output rating specified for any or all outputs of a power supply under specified conditions including duty cycle, period and amplitude. 2) The highest specified output power rating of a supply specified under worst case conditions.

MINIMUM LOAD

1) The lowest specified current to be drawn on a constant voltage power supply for the voltage to be in a specified range. 2) For a constant current supply, the maximum value of load resistance.

MODULAR

1) A physically descriptive term used to describe a power supply made up of a number of separate subsections, such as an input module, power module, or filter module. 2) An individual power unit patterned on standard dimensions and capable of being integrated with other parts or units into a more complex and higher power system.

MODULATOR

The control element of a switching power supply.

MOSFET

Abbreviation for Metal Oxide Semiconductor Field Effect Transistor.

MTBF

Abbreviation for Mean Time Between Failure.

N

NEGATIVE FEEDBACK:

1) (circuits and systems) The process by which part of the signal in the output circuit of an amplifying device reacts upon the input circuit in such a manner as to counteract the initial power, thereby decreasing the amplification. 2) (control) (industrial control) A feedback signal in a direction to reduce the variable that the feedback represents. 3)

GLOSSARY

(degeneration) (stabilized feedback) (data transmission)

The process by which a part of the power in the output circuit of an amplifying device reacts upon the input circuit in such a manner as to reduce the initial power, thereby reducing the amplification. (IEEE Std 100-1988)

NEGATIVE RAIL

The more negative of the two conductors at the output of a power supply.

NEGATIVE REGULATOR

A voltage regulator whose output voltage is negative compared to the voltage at the return.

NEGATIVE TEMPERATURE COEFFICIENT

A decreasing function with increasing temperature. The function may be resistance, capacitance, voltage, etc.

NODE

The junction of two or more branches in a circuit.

NOISE

The aperiodic random component on the power source output which is unrelated to source and switching frequency. Unless specified otherwise, noise is expressed in peak-to-peak units over a specified bandwidth.

NO LOAD VOLTAGE

Terminal voltage of battery or supply when no current is flowing in external circuit. See OPEN CIRCUIT VOLTAGE

NOMINAL VALUE

The stated or objective value of a quantity or component, which may not be the actual value measured.

NOMINAL VOLTAGE

The stated or objective value of a given voltage, which may not be the actual value measured.

O

OFF LINE POWER SUPPLY

1) A power supply in which the ac line is rectified and filtered without using a line frequency isolation transformer.
2) A power supply switched into service upon line loss to provide power to the load without significant interruption. See also UNINTERRUPTIBLE POWER SUPPLY.

OFFSET CURRENT

The direct current that appears as an error at either terminal of a dc amplifier when the input current source is disconnected.

OFFSET VOLTAGE

The dc voltage that remains between the input terminals of a dc amplifier when the output current voltage is zero

OHM

Unit of measure of resistance

OP-AMP

Abbreviation for Operational Amplifier

OHM

The difference in potential between the terminals of a cell or voltage when the circuit is open (no-load condition). See NO LOAD VOLTAGE.

OPEN-FRAME CONSTRUCTION

A construction technique where the supply is not provided with an enclosure.

OPEN LOOP

A signal path without feedback.

OPEN LOOP GAIN

Ratio of output signal to input signal without feedback.

OPERATING TEMPERATURE RANGE

The range of ambient, baseplate or case temperatures through which a power supply is specified to operate safely and to perform within specified limits. See also AMBIENT TEMPERATURE, STORAGE TEMPERATURE.

OPERATIONAL AMPLIFIER (OP-AMP)

A high gain differential input device that increases the magnitude of the applied signal to produce an error voltage.

OPERATIONAL POWER SUPPLY

A power supply with a high open loop gain regulator which acts like an operational amplifier and can be programmed with passive components.

OPTO-COUPLER

A package that contains a light emitter and a photoreceptor used to transmit signals between electrically isolated circuits.

OPTO-ISOLATOR

See OPTO-COUPLER.

OSCILLATOR

A nonrotating device for producing alternating current, the output frequency of which is determined by the characteristics of the device. (IEEE Std 100-1988)

GLOSSARY

OUTPUT

The energy or information delivered from or through a circuit or device.

OUTPUT CURRENT LIMITING

A protective feature that keeps the output current of a power supply within predetermined limits during overload to prevent damage to the supply or the load.

OUTPUT FILTER

One or more discrete components used to attenuate output ripple and noise.

OUTPUT IMPEDANCE

The impedance that a power supply appears to present to its output terminals.

OUTPUT IMPEDANCE

The specified range over which the value of a stabilized output quantity (voltage or current) can be adjusted.

OUTPUT RIPPLE AND NOISE

See PERIODIC and RANDOM DEVIATION.

OUTPUT VOLTAGE

The voltage measured at the output terminals of a power supply.

OUTPUT VOLTAGE ACCURACY

The tolerance in percent of the output voltage

OVERCURRENT DEVICE

A device capable of automatically opening an electric circuit, both under predetermined overload and short-circuit conditions, either by fusing of metal or by electromechanical means.

OVERCURRENT PROTECTION

See OUTPUT CURRENT LIMITING.

OVERLOAD PROTECTION

A feature that senses and responds to current of power overload conditions. See also OUTPUT CURRENT LIMITING.

OVERSHOOT

A transient change in output voltage in excess of specified output regulation limits, which can occur when a power supply is turned on or off, or when there is a step change in line or load.

OVERVOLTAGE

1) The potential difference between the equilibrium of an electrode and that of the electrode under an imposed polarization current. 2) A voltage that exceeds specified limits.

OVERVOLTAGE PROTECTION (OVP)

A feature that senses and responds to a high voltage condition. See also OVERVOLTAGE, CROWBAR.

OVP

Abbreviation for Overvoltage Protection.

P**PAD**

A conductive area on a printed circuit board used for connection to a component lead or terminal area, or as a test point.

PARALLEL

1) Term used to describe the interconnection of power sources in which like terminals are connected such that the combined currents are delivered to a single load.
2) The connection of components or circuits in a shunt configuration.

PARALLEL

The connection of two or more power sources of the same output voltage to obtain a higher output current. Special design considerations may be required for parallel operation of power sources.

PARD (periodic and random deviation):

Replaces the former term ripple of noise. PARD is the periodic and random deviation referring to the sum of all the ripple and noise components on the dc output of a power supply regardless of nature or source

PASS ELEMENT

A controlled variable resistance device, either a vacuum tube or semiconductor, in series with the dc power source used to provide regulation.

PEAK

Maximum value of a waveform reached during a particular cycle or operating time.

PEAK INVERSE VOLTAGE (PIV)

Maximum value of voltage applied in a reverse direction.

GLOSSARY

PEAK OUTPUT CURRENT

The maximum current value delivered to a load under specified pulsed conditions.

PEAK-TO-PEAK

The measured value of a waveform from peak in a positive direction to peak in a negative direction.

PERIODIC AND RANDOM DEVIATION (PARD)

The sum of all ripple and noise components measured over a specified band width and stated, unless otherwise specified, in peak-to-peak values.

PHASE ANGLE

The angle that a voltage waveform leads or lags the current waveform.

PIV

Abbreviation for Peak Inverse Voltage.

POLARITY

Property of device or circuit to have poles such as north and south or positive and negative.

POSITIVE RAIL

The most positive of the two output conductors of a power supply.

POST REGULATION

Refers to the use of a secondary regulator on a power supply output to improve line/load regulation and to attenuate ripple and noise.

POT

Abbreviation for potentiometer.

POTTING

An insulating material for encapsulating one or more circuit elements

POWER FACTOR

The ratio of true to apparent power expressed as a decimal, frequently specified as lead or lag of the current relative to voltage.

POWER FACTOR CORRECTION

1) Technique of forcing current draw to approach being in-phase with the voltage in an ac circuit. 2) Addition of capacitors to an inductive circuit to offset reactance.

POWER RATING

Power available at the output terminals of a power source based on the manufacturers specifications.

POWER SOURCE

Any device that furnishes electrical power, including a generator, cell, battery, power pack, power supply, solar cell, etc.

POWER SUPPLY

A device for the conversion of available power of one set of characteristics to another set of characteristics to meet specified requirements. Typical application of power supplies include to convert raw input power to a controlled or stabilized voltage and/or current for the operation of electronic equipment.

POWER SUPPLY CORD

An assembly of a suitable length of flexible cord provided with an attachment plug at one end.

PPM

Abbreviation for parts per million.

PREREGULATION

The initial regulation circuit in a system containing at least two cascade regulation loops.

PRIMARY-SIDE-CONTROL

A name for an off-line switching power supply with the pulse-width modulator in the primary.

PREREGULATION

A circuit electrically connected to the input or source of power to the device.

PROGRAMMABLE COEFFICIENT

The required range in control resistance to produce a one volt change in output voltage. Expressed in ohms per volt. The ratio of change in a control parameter to induce a unit change in an output, e.g., 100 ohms/volt, or 100 ohms/ampere.

PROGRAMMABLE POWER SUPPLY

A power supply with an output controlled by an applied voltage, current, resistance or digital code.

PROGRAMMING

The control of a power supply parameter, such as output voltage, by means of a control element or signal.

PULSE-WIDTH MODULATION (PWM)

A method of regulating the output voltage of a switching power supply by varying the duration, but not the frequency, of a train of pulses that drives a power switch.

GLOSSARY

PULSE-WIDTH MODULATOR (PWM)

An integrated discrete circuit used in switching-type power supplies, to control the conduction time of pulses produced by the clock.

PUSH-PULL CIRCUIT

A circuit containing two like elements that operate in 180-degree phase relationship to produce additive output components of the desired wave, with cancellation of certain unwanted products. Note: Push-pull amplifiers and push-pull oscillators are examples. (IEEE Std 100-1988)

PUSH-PULL CONVERTER

A power switching circuit that uses two or more power switches driven alternately on and off.

PWM

Variously, the abbreviation for Pulse-Width Modulation, Pulse-Width Modulator

R

RATED OUTPUT CURRENT

The maximum continuous load current a power supply is designed to provide under specified operating conditions.

RECOVERY TIME

The time required for the measured characteristic to return to within specified limits following an abnormal event.

RECTIFICATION

The process of changing an alternating current to a unidirectional current. See FULL-WAVE RECTIFIER, HALF-WAVE RECTIFIER.

RECTIFIER

A component that passes current only in one direction, e.g., a diode.

REFERENCE GROUND

Defined point in a circuit or system from which potential measurements shall be made.

REFERENCE VOLTAGE

The defined or specified voltage to which other voltages are compared.

REGULATED POWER SUPPLY

A device that maintains within specified limits a constant output voltage or current for specified changes in line, load temperature or time.

REGULATION

The process of holding constant selected parameters, the extent of which is expressed as a percent.

REGULATOR

The power supply circuit that controls or stabilizes the output parameter at a specified value.

REMOTE CONTROL

1) (general) Control of an operation from a distance: this involves a link, usually electrical, between the control device and the apparatus to be operated. Note: Remote control may be over (A) direct wire, (B) other types of interconnecting channels such as carrier-current or microwave, (C) supervisory control, or (D) mechanical means. 2) (programmable instrumentation) A method whereby a device is programmable via its electrical interface connection in order to enable the device to perform different tasks. (IEEE Std 100-1988)

REMOTE PROGRAMMING

See PROGRAMMING.

REMOTE SENSING

A technique for regulating the output voltage of a power supply at the load by connecting the regulator error-sensing leads directly to the load. Remote sensing compensates for specified maximum voltage drops in the load leads. Care should be exercised to avoid opening load handling leads to avoid damaging the power supply. Polarity must be observed when connecting sense leads to avoid damaging the system.

REPEATABILITY

The ability to duplicate results under identical operating conditions.

RESET SIGNAL

A signal used to return a circuit to a desired state.

RESISTANCE (R)

Property of a material that opposes the flow of current.

RESOLUTION

The smallest increment of change in output that can be obtained by an adjustment.

RESONANCE

1) The state in which the natural response frequency of a circuit coincides with the frequency of an applied signal, or vice versa, yielding intensified response. 2) The state in which the natural vibration frequency of a body coincides with an applied vibration force, or vice versa, yielding reinforced vibration of the body.

GLOSSARY

RESONANT CIRCUIT

A circuit in which inductive and capacitive elements are in resonance at an operating frequency.

RESONANT CONVERTER

A class of converters that uses a resonant circuit as part of the regulation loop.

RESONANT FREQUENCY

The natural frequency at which a circuit oscillates or a device vibrates. In an L-C circuit, inductive and capacitive reactances are equal at the resonant frequency.

RESPONSE TIME

The time required for the output of a power supply or circuit to reach a specified fraction of its new value after step change or disturbance.

RETURN

The name for the common terminal of the output of a power supply; it carries the return current for the outputs.

REVERSE VOLTAGE PROTECTION

A circuit or circuit element that protects a power supply from damage caused by a voltage of reverse polarity applied at the input or output terminals.

RFI

Abbreviation for Radio Frequency Interference.

RIDE-THROUGH

See HOLDUP TIME

RIPPLE

The periodic ac component at the power source output harmonically related to source or switching frequencies. Unless specified otherwise, it is expressed in peak-to-peak units over a specified band width.

RIPPLE AND NOISE

See PERIODIC and RANDOM DEVIATION (PARD). See PERIODIC and RANDOM DEVIATION (PARD).

RIPPLE VOLTAGE

The periodic ac component of the dc output of a power supply.

RISE TIME

The time required for a pulse to rise from 10 percent to 90 percent of its maximum amplitude.

RMS VALUE

In text, use lower case: rms. Abbreviation for Root Mean Square Value.

ROOT MEAN SQUARE (RMS) VALUE

- 1) (periodic function) The square root of the average of the square of the value of the function taken throughout one period (IEEE Std 100-1988).
- 2) For a sine wave, $0.707 \times \text{Peak Value}$.

S

SAFE OPERATING AREA (SOA)

A manufacturer specified power/time relationship that must be observed to prevent damage to power bipolar semiconductors.

SAFETY COMPLIANCE

Certification, recognition or approval by safety agencies such as Underwriters Laboratories Inc. (UL/U.S.A.), Canadian Standards Association (CSA), etc. See also COMPLIANCE.

SAFETY GROUND

A conductive path from a chassis, panel or case to earth to help prevent injury or damage to personnel and equipment.

SCR

Abbreviation for Silicon-Controlled Rectifier.

SECONDARY CIRCUIT

A circuit electrically isolated from the input or source of power to the device.

SECONDARY OUTPUT

An output of a switching power supply that is not sensed by the control loop.

SENSE AMPLIFIER

An amplifier which is connected to the output voltage divider to determine, or sense, the output voltage. (Bertan High Voltage)

SENSE LINE

The conductor which routes output voltage to the control loop. See also REMOTE SENSING.

SENSE LINE RETURN

The conductor which routes the voltage on the output return to the control loop. See also REMOTE SENSING.

GLOSSARY

SEQUENCING

The process that forces the order of turn on and turn off of individual outputs of a multiple output power supply.

SERIES

1) The interconnection of two or more power sources such that alternate polarity terminals are connected so their voltages sum at a load. 2) The connection of circuit components end to end to form a single current path.

SERIES PASS

A controlled active element in series with a load that is used to regulate voltage.

SERIES REGULATOR

A regulator in which the active control element is in series with the dc source and the load.

SERIES REGULATION

See LINEAR REGULATION

SETTING RANGE

The range over which the value of the stabilized output quantity may be adjusted.

SETTING TIME

The time for a power supply to stabilize within specifications after an excursion outside the input/output design parameters.

SHIELD

Partition or enclosure around components in a circuit to minimize the effects of stray magnetic and radio frequency fields. See also ENCLOSURE, ELECTROSTATIC SHIELD, FARADAY SHIELD.

SHOCK HAZARD

A potentially dangerous electrical condition that may be further defined by various industry or agency specifications.

SHORT CIRCUIT

A direct connection that provides a virtually zero resistance path for current.

SHORT CIRCUIT

The initial value of the current obtained from a power source in a circuit of negligible resistance

SHORT CIRCUIT PROTECTION

A protective feature that limits the output current of a power supply to prevent damage.

SHORT CIRCUIT TEST

A test in which the output is shorted to ensure that the short circuit current is within its specified limits.

SHUNT

1) A parallel conducting path in a circuit. 2) A low value precision resistor used to monitor current.

SHUNT REGULATOR

A linear regulator in which the control element is in parallel with the load, and in series with an impedance, to achieve constant voltage across the load.

SI

Abbreviation for System International d'Unites.

SIGNAL GROUND

The common return or reference point for analog signals.

SINE WAVE

A wave form of a single frequency alternating current whose displacement is the sine of an angle proportional to time or distance.

SLAVE

A power supply which uses the reference in another power supply, the master, as its reference

SLEW RATE

The maximum rate of change a power supply output can produce when subjected to a large step response or specified step change. The power supply is turned on.

SLOW START

A feature that ensures the smooth, controlled rise of the output voltage, and protects the switching transistors from transients when the power supply is turned on.

SNUBBER

An RC network used to reduce the rate of rise of voltage in switching applications

SOA

Abbreviation for Safe Operating Area.

SOFT STARTS

Controlled turn on to reduce inrush currents.

SOURCE

Origin of the input power, e.g., generator, utility lines, mains, batteries, etc.

GLOSSARY

T

SOURCE VOLTAGE EFFECT

The change in stabilized output produced by a specified primary source voltage change.

STABILITY

1) The percent change in output parameter as a function of time, with all other factors constant, following a specified warm-up period. 2) The ability to stay on a given frequency or in a given state without undesired variation.

STANDOFF

A mechanical support, which may be an insulator, used to connect and support a wire or device away from the mounting surface.

STEP-DOWN TRANSFORMER

(power and distribution transformer) A transformer in which the power transfer is from a higher voltage source circuit to a lower voltage circuit. (IEEE Std 100-1988)

STEP-UP TRANSFORMER

(power and distribution transformer) A transformer in which the power transfer is from a lower voltage source circuit to a higher voltage circuit. (IEEE Std 100-1988)

STORAGE TEMPERATURE

The range of ambient temperatures through which an inoperative power supply can remain in storage without degrading its subsequent operation. See also AMBIENT TEMPERATURE, OPERATING TEMPERATURE.

SUMMING POINT

The point at which two or more inputs of an operational amplifier are algebraically added.

SWITCHING FREQUENCY

The rate at which the dc voltage is switched in a converter or power supply.

SWITCHING FREQUENCY

A switching circuit that operates in a closed loop system to regulate the power supply output.

SYNCHRONOUS RECTIFICATION

A rectification scheme in a switching power supply in which a FET or bipolar transistor is substituted for the rectifier diode to improve efficiency.

SYSTEME INTERNATIONAL d'UNITES (SI)

The International System of Units comprised of Base Units, Supplementary Units and Derived Units.

TRANSIENT RESPONSE TIME

The room temperature or temperature of the still air surrounding the power supply, with the supply operating.

TEMPERATURE COEFFICIENT

The average percent change in output voltage per degree centigrade change in ambient temperature over a specified temperature range. See also AMBIENT TEMPERATURE.

TEMPERATURE DERATING

The amount by which power source or component ratings are decreased to permit operation at elevated temperatures.

TEMPERATURE EFFECT

See TEMPERATURE COEFFICIENT.

TEMPERATURE RANGE, OPERATING

See OPERATING TEMPERATURE RANGE

THERMAL PROTECTION

A protective feature that shuts down a power supply if its internal temperature exceeds a predetermined limit.

THREE TERMINAL REGULATOR

A power integrated circuit in a 3-terminal standard transistor package. It can be either a series or shunt regulator IC.

TIME CONSTANT

Time period required for the voltage of a capacitor in an RC circuit to increase to 63.2 percent of maximum value or decrease to 36.7 percent of maximum value.

TOLERANCE

Measured or specified percentage variation from nominal.

TOTAL EFFECT

The change in a stabilized output produced by concurrent worst case changes in all influence quantities within their rated range.

TRACE

A conducting path on a printed circuit board.

TRACKING

A characteristic of a multiple-output power supply that describes the changes in the voltage of one output with respect to changes in the voltage or load of another.

GLOSSARY

TRACKING REGULATOR

A plus or minus two-output supply in which one output tracks the other.

TRANSIENT

An excursion in a given parameter, typically associated with input voltage or output loading.

TRANSIENT EFFECT

The result of a step change in an influence quantity on the steady state values of a circuit.

TRANSIENT RECOVERY TIME

The time required for the output voltage of a power supply to settle within specified output accuracy limits following a transient.

TRANSIENT RESPONSE

Response of a circuit to a sudden change in an input or output quantity.

TRANSIENT RESPONSE TIME

The interval between the time a transient is introduced and the time it returns and remains within a specified amplitude range.

TTL

Abbreviation for transistor-transistor logic

U

UL

Abbreviation for Underwriters Laboratories Incorporated.

UNDERSHOOT

A transient change in output voltage in excess of specified output regulation limits. See OVERSHOOT.

UNDERVOLTAGE PROTECTION

A circuit that inhibits the power supply when output voltage falls below a specified minimum.

UNDERWRITERS LABORATORIES INCORPORATED (UL)

American association chartered to test and evaluate products, including power sources. The group has four locations so an applicant can interact with the office closest in the country to his/her own location.

UNINTERRUPTIBLE POWER SUPPLY (UPS)

A type of power supply designed to support the load for specified periods when the line varies outside specified limits. See also OFF LINE POWER SUPPLY, ON LINE POWER SUPPLY.

UPS

Abbreviation for Uninterruptible Power Supply.

V

VARISTOR

A two electrode semiconductor device having a voltage-dependent nonlinear resistance.

VDE

Abbreviation for Verband Deutscher Elektrotechniker.

VOLTAGE DIVIDER

Tapped or series resistance or impedance across a source voltage to produce multiple voltages.

VOLTAGE DOUBLER

See VOLTAGE MULTIPLIER.

VOLTAGE DROP

Difference in potential between two points in a passive component or circuit.

VOLTAGE LIMIT

Maximum or minimum value in a voltage range.

VOLTAGE LIMITING

Bounding circuit used to set specified maximum or minimum voltage levels.

VOLTAGE MODE

The functioning of a power supply so as to produce a stabilized output voltage.

VOLTAGE MONITOR

A circuit or device that determines whether or not an output voltage is within some specified limits.

VOLTAGE MULTIPLIER

Rectifier circuits that produce an output voltage at a given multiple greater than input voltage, usually doubling, tripling, or quadrupling.

GLOSSARY

VOLTAGE REGULATION

The process of holding voltage constant between selected parameters, the extent of which is expressed as a percent. See also REGULATION.

VOLTAGE SOURCE

A power source that tends to deliver constant voltage.

VOLTAGE STABILIZATION

The use of a circuit or device to hold constant an output voltage within given limits

VOLT (V)

Unit of measurement of electromotive force or potential difference. Symbol E, in electricity; symbol V in semiconductor circuits.

W

WARMUP

Process of approaching thermal equilibrium after turn on.

WARMUP DRIFT

The change in output voltage of a power source from turn on until it reaches thermal equilibrium at specified operating conditions.

WARMUP EFFECT

Magnitude of change of stabilized output quantities during warmup time.

WARMUP TIME

The time required after a power supply is initially turned on before it operates according to specified performance limits.

WATT (W)

Unit of measure of power equal to 1 joule/sec. ($W=EI$)

WEBER (Wb)

The SI unit of magnetic flux equal to 108 maxwells. The amount of flux that will induce 1 volt/turn of wire as the flux is reduced at a constant rate to zero over a period of one second.

WITHSTAND VOLTAGE

The specified operating voltage, or range of voltages, of a component, device or cell.

WORKING VOLTAGE

The specified operating voltage, or range of voltages, of a component, device or cell.

WORST CASE CONDITION

A set of conditions where the combined influences on a system or device are most detrimental.

X

X-RAY TUBE

A vacuum tube designed for producing X-rays by accelerating electrons to a high velocity by means of an electrostatic field and then suddenly stopping them by collision with a target. (IEEE Std 100-1988)

Z

ZENER DIODE

1) A diode that makes use of the breakdown properties of a PN junction. If a reverse voltage across the diode is progressively increased, a point will be reached when the current will greatly increase beyond its normal cut-off value to maintain a relatively constant voltage. Either voltage point is called the Zener voltage. 2) The breakdown may be either the lower voltage Zener effect or the higher voltage avalanche effect.

ZENER VOLTAGE

The reverse voltage at which breakdown occurs in a zener diode.

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