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Power-Based Arbitrary Waveform Generator

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**POWER
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Power Electronics & Energy Storage event
27 juni 2023 | 1931 Congrescentrum 's-Hertogenbosch

ENERGY STORAGE

Overview

- Certain manufacturing processes require very fast programming and output load transient response, along with tight accuracy from the power source feeding the process
 - ✓ Semiconductor laser applications can require pulse currents in the 100's of amperes with transition rates on the order of 1000A/ms
 - ✓ Pulse plating and beam steering applications may require bipolar currents with both fast transient times and tight accuracy requirements
- The objective of this paper is to explore off-line power sources which can support output slew rates at or above these requirements (>[200V/ms](#); >[1000A/ms](#))

Semiconductor Lasers:



Pulse Plating:



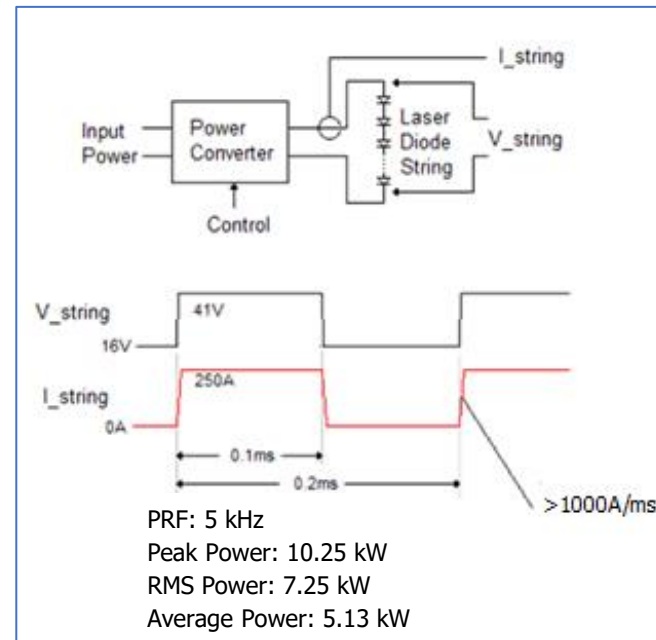
Beam Steering:



Limitations on Delivered Slews Rates

- In order to provide DC power, off-line power supplies must be able to filter out AC line frequency signals
- This generally results in an output capacitor which limits how fast the output voltage can change in response to a change in conditions
- This can limit response time in applications which require fast slew rates of either delivered voltage or delivered current

Semiconductor Lasers:



Pulse Plating:

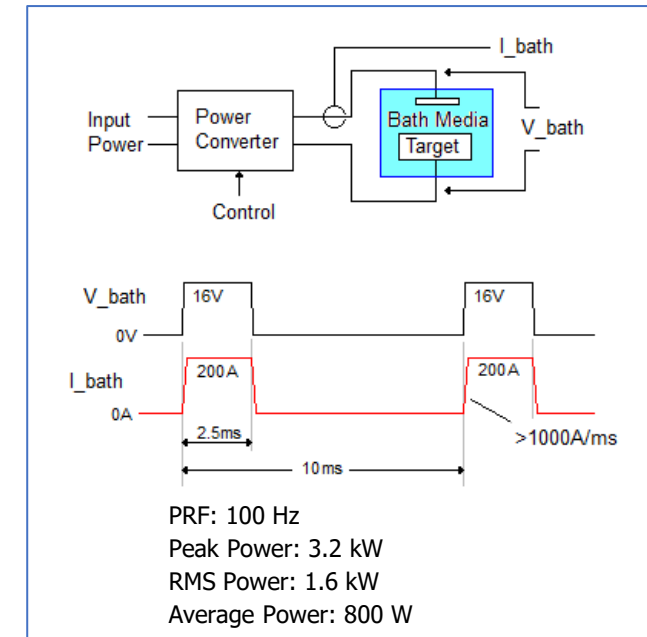
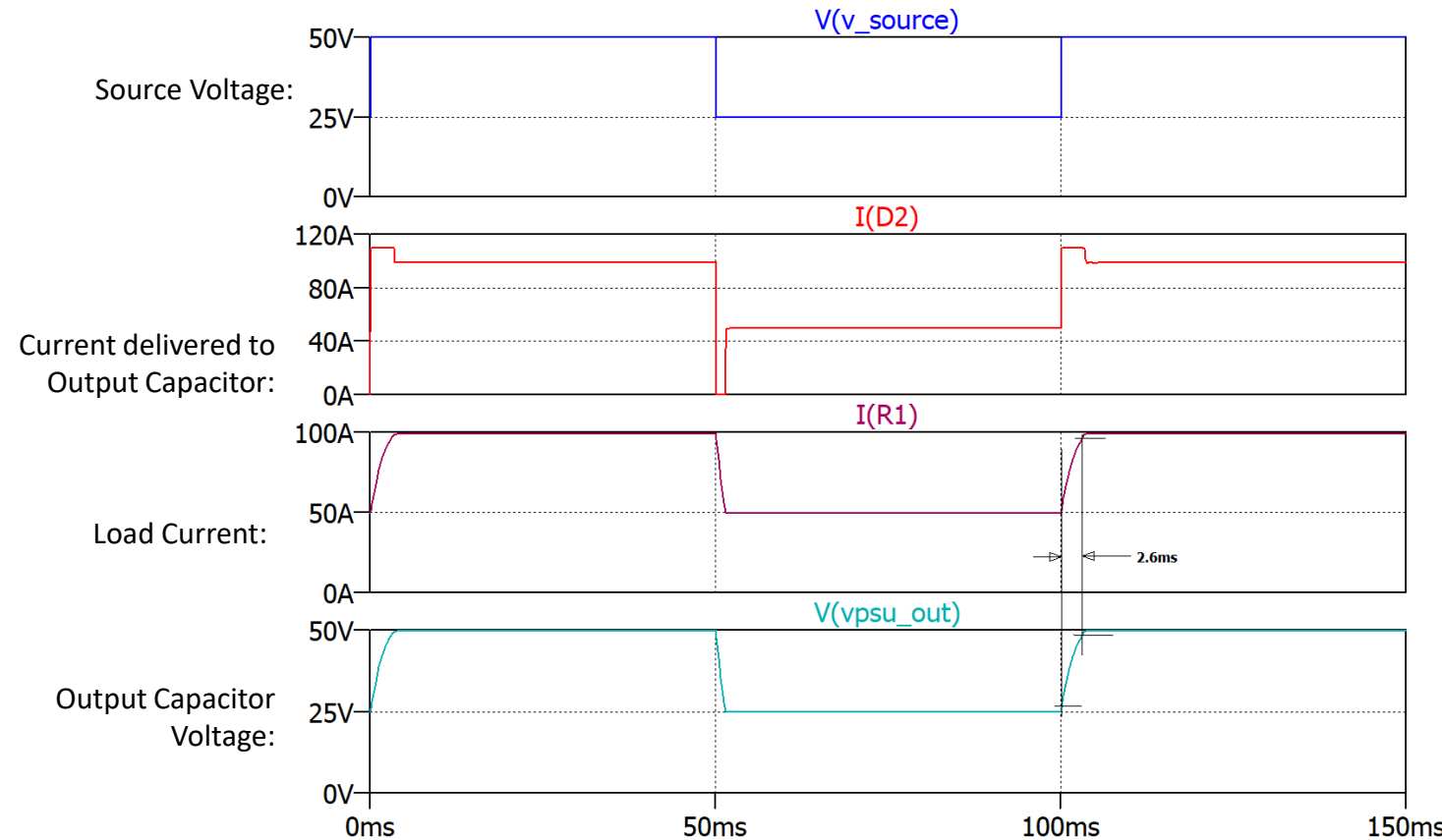
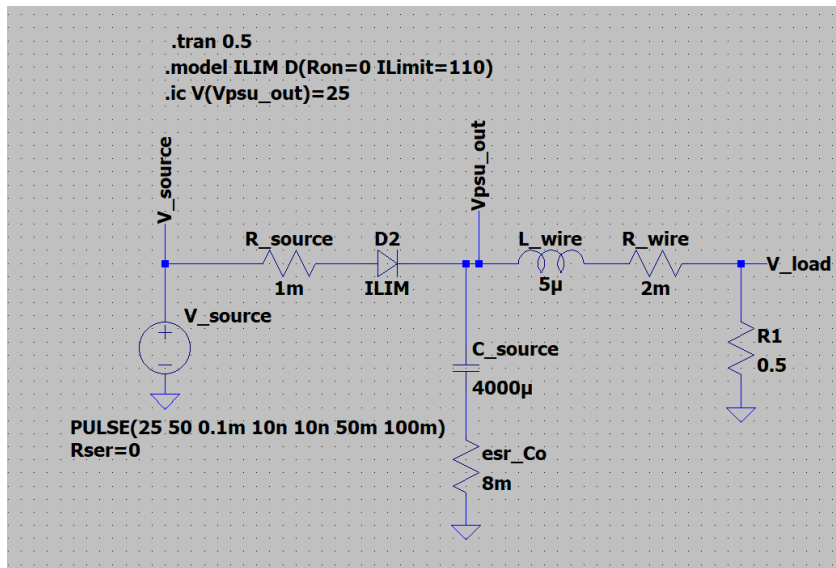
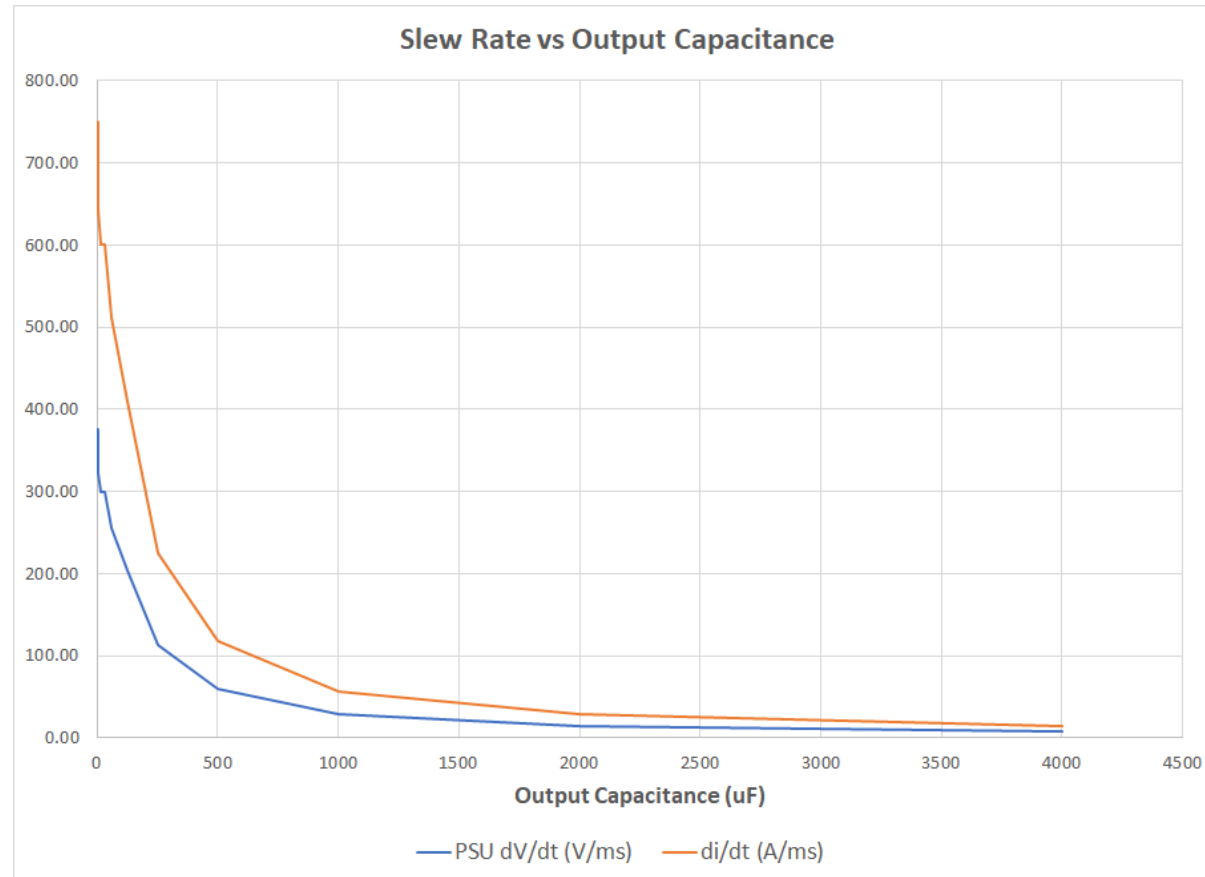


Illustration of Typical Off-Line PSU Output Capacitor Effects

- LTspice simulation demonstrating effects of typical 5kW (50V/100A) off-line PSU output filter and over-current protection circuits on delivered slew rate
 - ✓ Assumes instantaneous response of control loop and main voltage generator
 - ✓ Output filter capacitor = 4000uF
 - ✓ OCP set at 110A for a 100A rated PSU
 - ✓ 10uH of load cable inductance
- Program output from 25V to 50V
 - ✓ Delivered rise time = 2.6ms - output slew rate 15A/ms



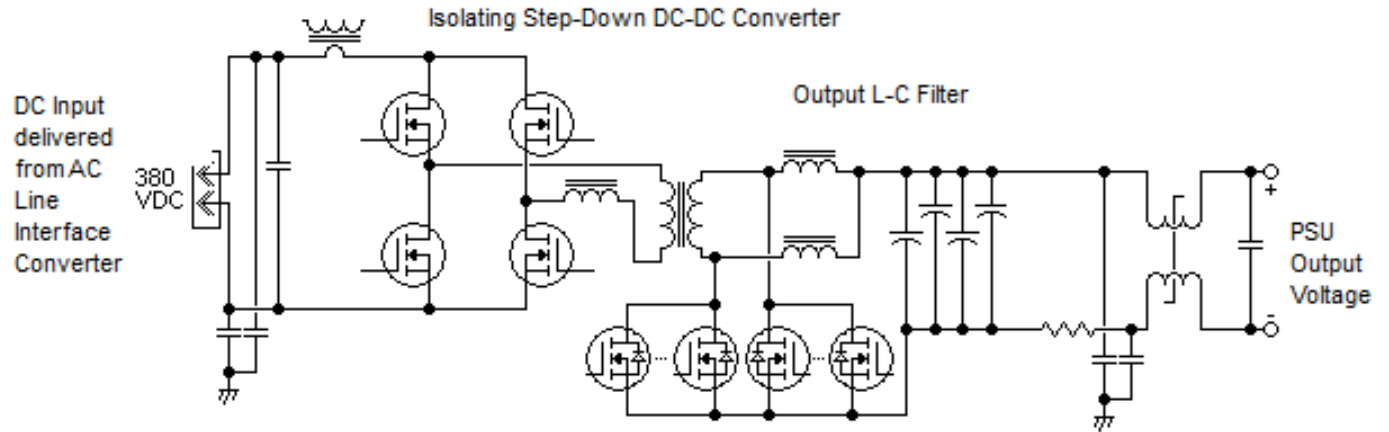
Effects of PSU Output Capacitance on Slew Rate



- Reducing PSU output capacitance has a dramatic effect on achievable slew rates
- Reducing output capacitance by ~90% from what is typically found in off-line power supplies enables slew rates >200V/ms

Additional Considerations on High Slew Rate

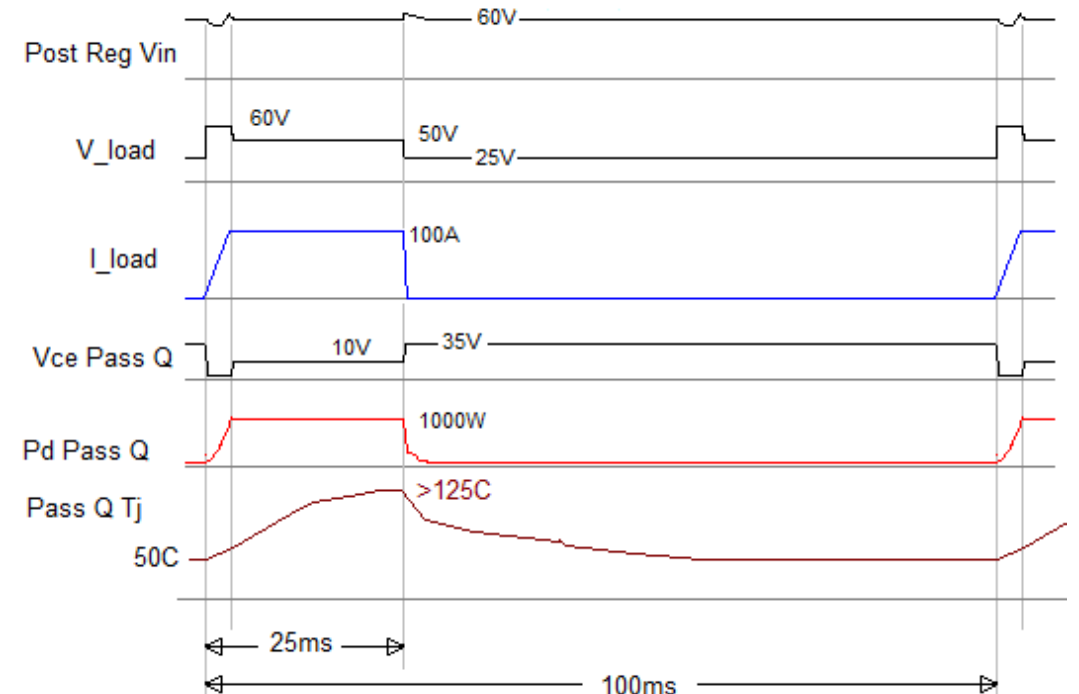
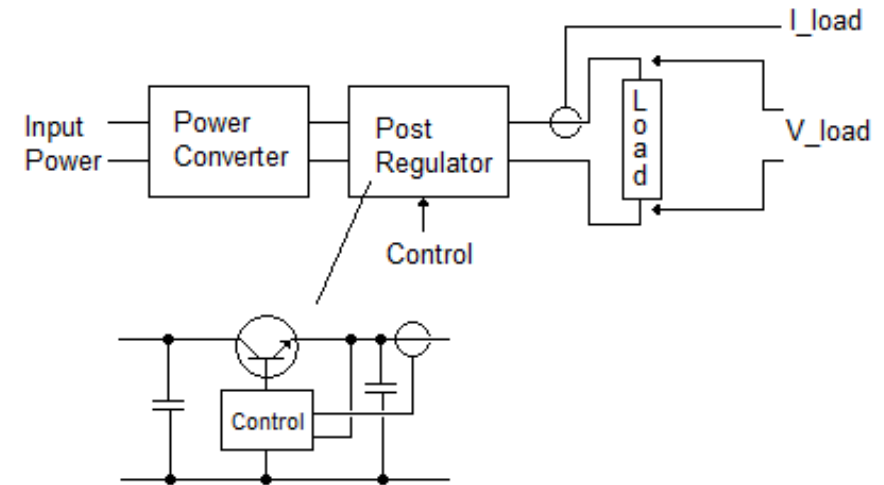
High Frequency Switch Mode Converter:



- Impediments to High Slew Rates:
 - ✓ Output capacitor limits output discharge time
 - ✓ Output choke limits output charge time
 - ✓ Control loop limits response time
- Supplies operating from AC power line generally need a significant output filter (L+C) and control loop with a modest gain crossover bandwidth in order to suppress ripple and provide stable operation – this limits their ability to support ultra-high slew rate applications
 - ✓ These typically limit maximum dynamic output frequency to 10Hz, or less, and output slew rate to <math><10\text{V/ms}</math> or 100A/ms

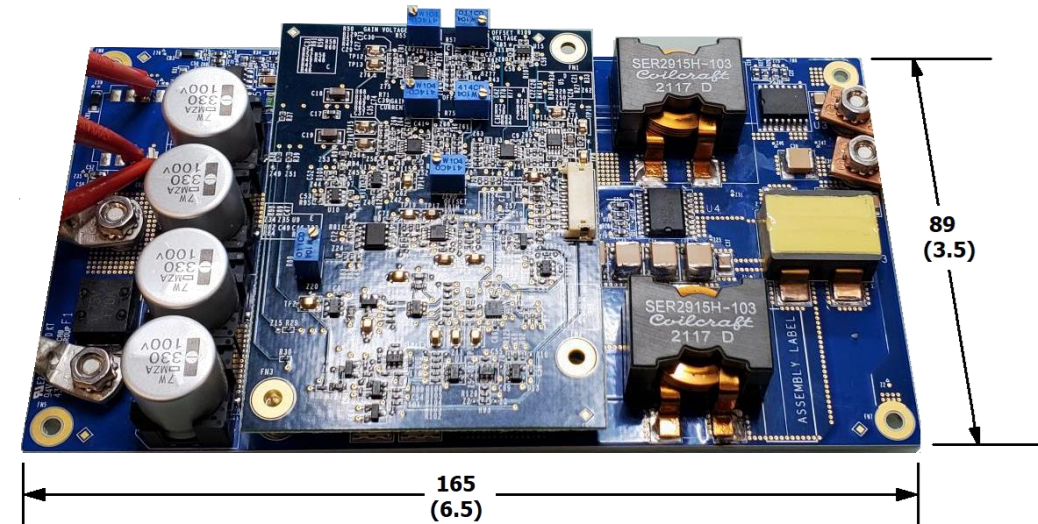
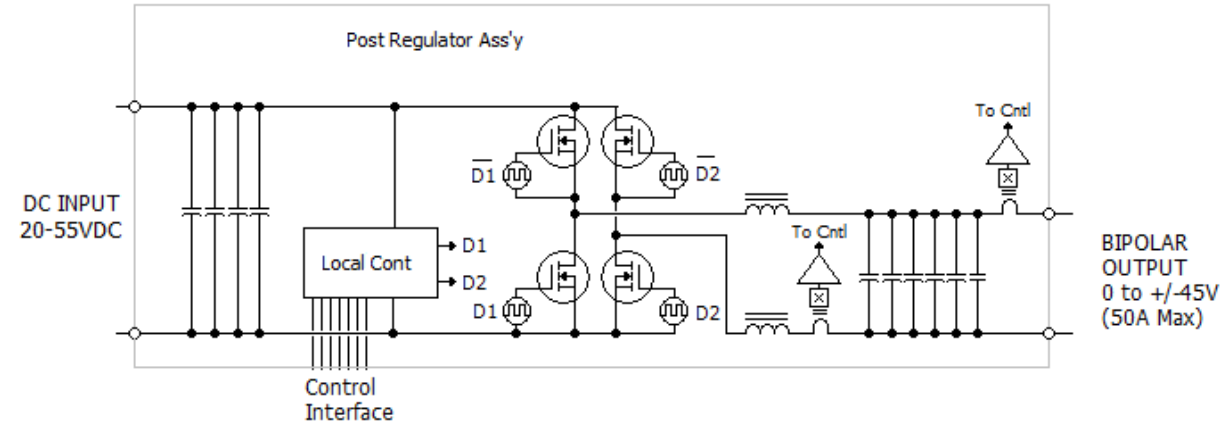
Solving the Problem

- Providing a high bandwidth post regulator with minimal output capacitance has been one method employed
 - ✓ Typically, a transistor-based linear pass regulator is employed
- Voltage and current delivered to the load are monitored and transistor conduction is adjusted to optimize output current delivery
 - ✓ This topology places a heavy burden on the pass transistor as it must block the difference between the AC-DC PSU output and load voltage while also passing all the load current
 - ✓ As illustrated, extremely high operating temperatures may result



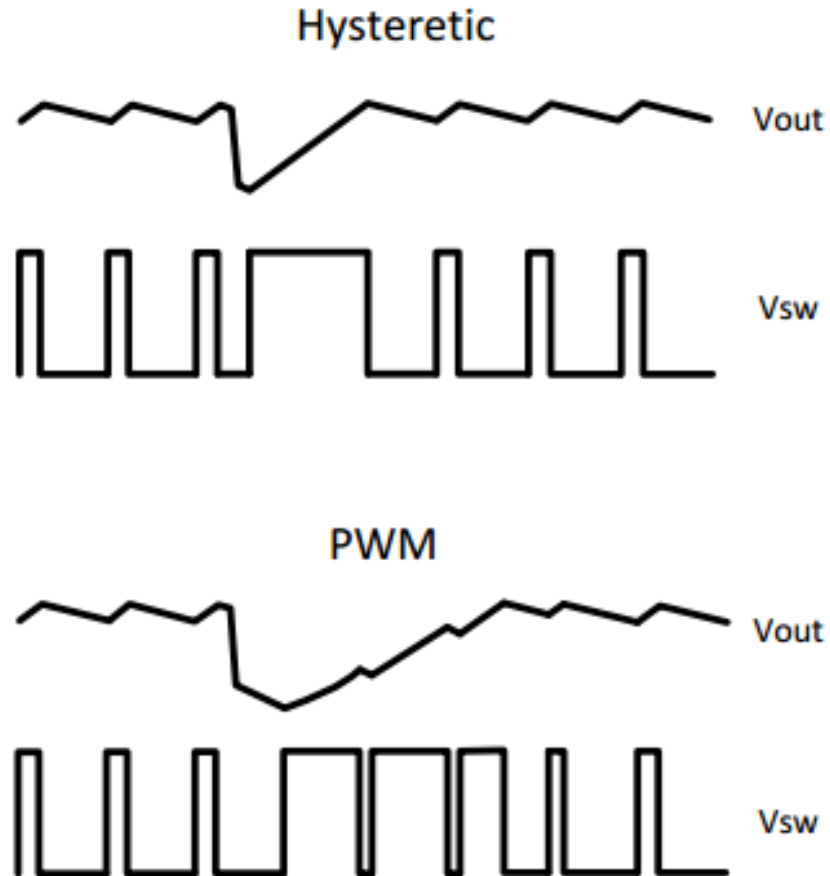
Optimizing the Post Regulator

High Frequency Switch Mode Post Regulator:



- The converter which supports high slew rates must feature a fast control loop response time, minimal output capacitance and minimal filtering inductance
- This challenge can be met with a high-speed Hysteretic-control high frequency switch mode post converter connected between the AC-DC power supply and load
- The converter provides a bipolar output which is often required for plating and beam steering applications
- Baseline building block which delivers up to 40V and up to 50A per "brick"
 - ✓ Minimal output capacitance and filter inductance delivers >1000V/ms; 2000A/ms output
- Very high efficiency >98%
- Compact size - Converters can be modular and scalable

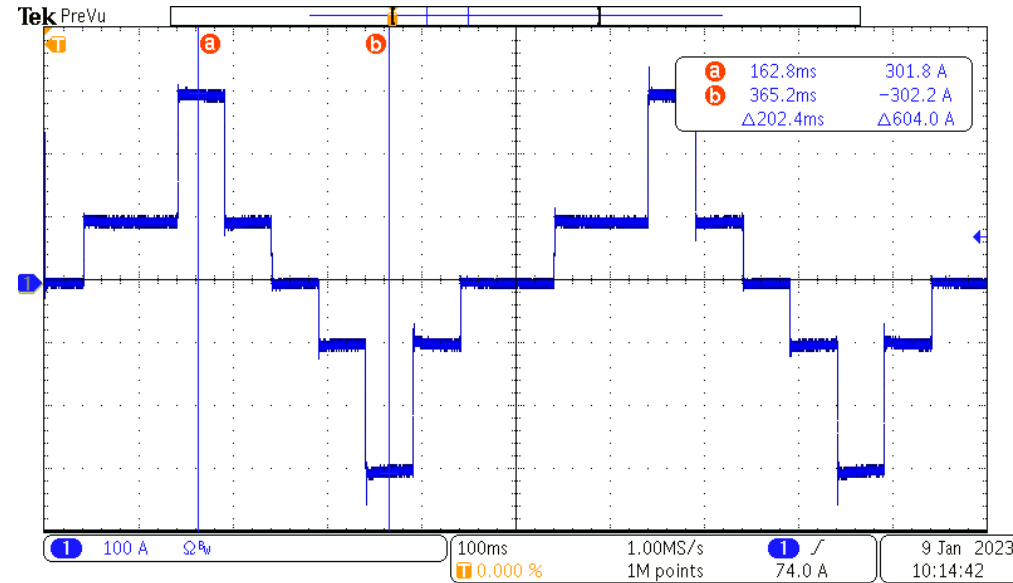
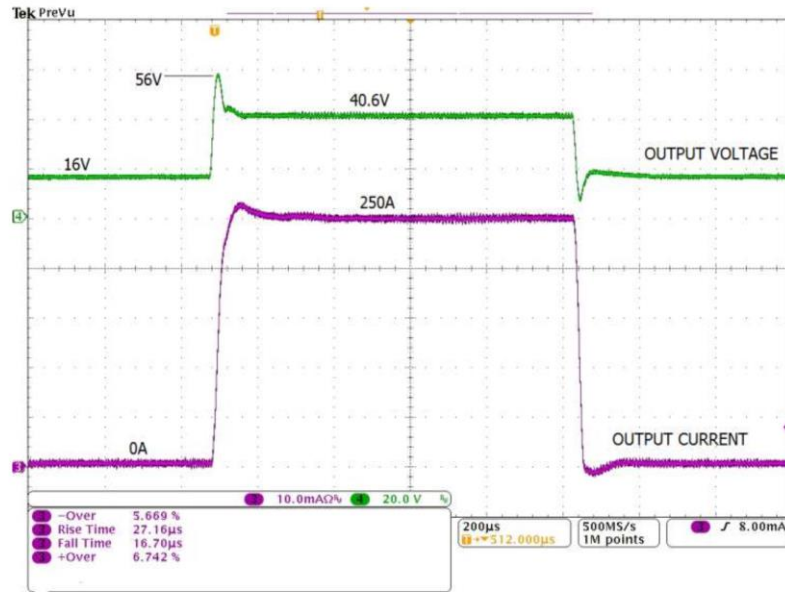
Hysteretic Converter Control



- **Advantages of Hysteretic Control:**
- Unlike pulse width modulated power supplies, the slew rate of a Hysteretic controlled converter is not limited to its closed loop bandwidth
 - ✓ Allows for faster output current rise time compared to traditional PWM control.
- The minimum rise time is set by the output inductor and input voltage overhead.
 - ✓ Since the slew rate doesn't depend on control loop bandwidth, the switching frequency range can be selected to achieve the best efficiency at different load conditions.

Achievable Performance Examples

0 – 250A Into Diode Load / 5kHz Rep Rate



8 assemblies connected in parallel
in a semiconductor laser application

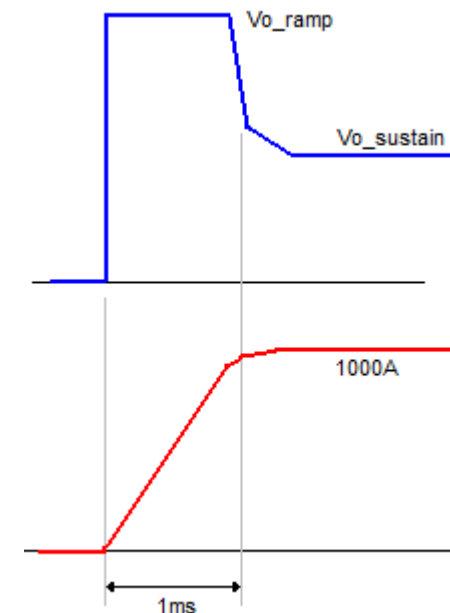
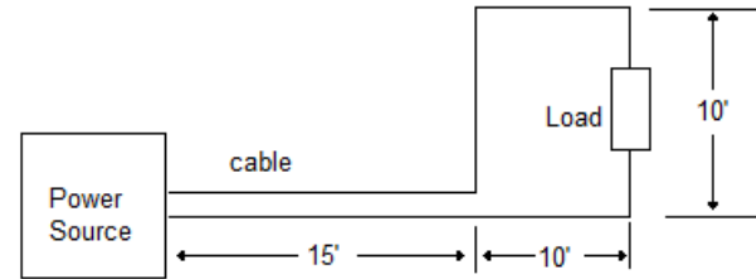
- Slew rate >4000A/ms

3 assemblies connected in parallel in a pulse plating application

- Programmable bi-polar output
- Output commanded from 0 to +100 to +300 to +100 to 0 to -100 to -300 to -100 to 0A (500ms period = 2Hz)

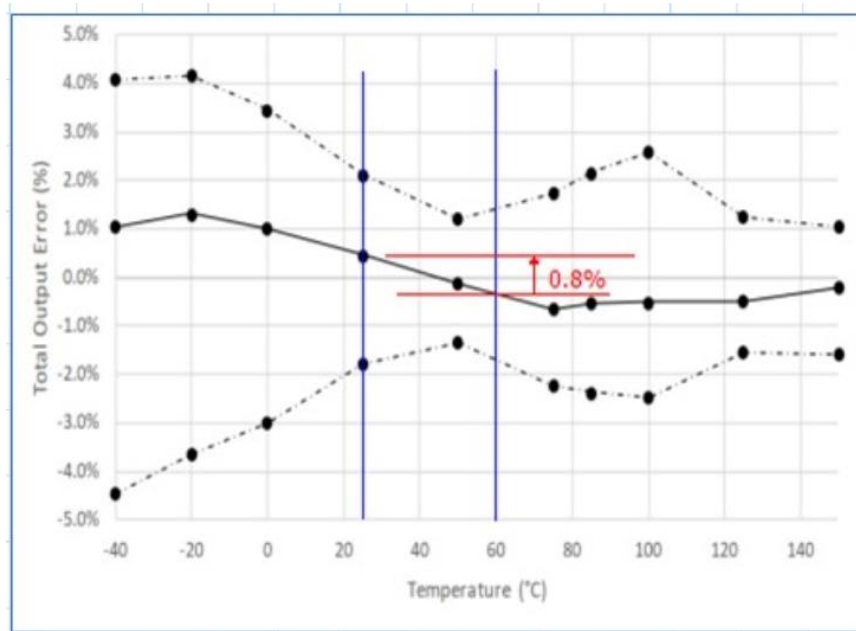
Overcoming Connection Inductance

- Connection Inductance to the load can limit current rise time
- Typical inductance estimated to be on the order of 15uH, or higher
- Any inductance inherent in the converter will add to this
- In order to achieve rise time to 2000A in <1ms, power supply source voltage must be well above voltage required to sustain load
- ✓ This typically sets the minimum link voltage between the AC-DC converter and AWG



Delivered Current Accuracy

Hall Effect Sensor Error vs. Temperature:



- AWG utilizes high quality Hall Effect sensors for delivered current control and measurement
 - ✓ Initial tolerance zero output offset calibrated to within +/-10mA (0.02% of 50A)
 - ✓ Initial tolerance gain slope calibrated so that $I_{max} = 50A$ within 100mA (0.2%)
- Temperature rise of Hall Effect sensor can result in an additional 0.8% error at full output power over operational temperature range
- Typical resolution for a 12-bit system = 25mA per bit
 - ✓ Increased resolution achievable with higher bandwidth control interfaces

Realized AC to High-Speed Pulse System



- **Wide Range Output** 0-40V / 0 to +/-50A Output (2kW max)
- **AC Input** 200-240VAC, 1ph or 380-480VAC, 3ph
- **Fast Slew Rate** 2,000V/ms, / 1,000A/ms*
- **Output Pulse Frequency** Up to 5kHz
- **Operating Modes** Constant Voltage / Constant Current
- **Output Polarity** Forward or Reverse Pulsing
- **High Reliability** 100% HASS Tested
- **Compact Size** 1U 19" Rack Mount – 16.5" (419mm) depth
- **Remote Control** Analog plus high-speed serial digital interface
- **Cooling** Fan Cooled

Astrodyne TDI's Hermes High Speed Pulse Converter provides industrial grade DC pulsed power for semiconductor manufacturing, medical imaging, test & burn in, and other process power applications requiring exceptionally fast programming and response times. With output slew rates up to 1000A/us*, this **LiquaCore** regulator is the ideal choice for applications demanding high slew rates and precise control.

Housed in a compact 1U high chassis, reliability is assured through our rigorous design process, component de-rating in accordance with NAVSO P-3641A, and 100% Highly Accelerated Stress Screening (HASS) test as part of their production process.

Operating from either 240V, 1-ph or 480V, 3-ph input, along with output programmability via a high-speed serial digital interface, this product provides a versatile solution for process applications.

* Driving a load with 20uH series inductance with 60V Input

Specifications:

DC INPUT

Input Voltage: 200-240VAC, 1ph or 380-480V, 3-ph Delta (47-63Hz)
Input Current: 12.2A max at 200VAC, 1ph or 4A max at 380VAC, 3ph
Efficiency: 89% (200-240VAC input)
 84% (380-480VAC input)

OUTPUT

Operating Modes: User selectable Constant Voltage or Constant Current
Output Programming: Output V or I instantaneous value can be programmed in near real time (< 1ms latency) or a time varying script can be loaded and executed upon command
Program Resolution: Current Mode: 20mA per bit*
 Voltage Mode: 25mV per bit
 Adjustable from -40V to +40V
Output Voltage: -50A to +50A
Output Current: 2,000W Maximum
Output Power Mode: Output can be programmed in CC mode at currents between -Io(max) and +Io(max) at frequencies up to 5-kHz

CONSTANT VOLTAGE MODE:

Load Regulation: 0.25% of Vo(max) from no load to full rated load
Line Regulation: Less than 0.25% of Vo(max) over low line to high line conditions
Output Ripple: Less than 0.25Vpk-pk, 100mV(rms) – 20MHz measurement bandwidth
Programming Accuracy: +/-0.1V of commanded voltage
Temperature Coeff: Less than 250ppm/°C

CONSTANT CURRENT MODE:

Load Regulation: Programmed current will vary less than 0.1A (0.2% of maximum rated current)
Programming Accuracy: +/-1mA or 1% of command current, whichever is lower
Temperature Coeff: Less than 250ppm/°C

* Increased resolution can be made available – consult factory

PROTECTION FEATURES

Output over-current: Constant current circuit with automatic crossover limits delivered current to user settable value.
Over-temperature: Over-temperature protection shuts unit down if excessive temperature is detected.

ALARMS AND CONTROL

Remote Control: Analog, plus options for Ethernet, CANCAT, Devcon, or RS232

ENVIRONMENTAL CONDITIONS

Cooling: Forced Air Cooled
Ambient Temperature: -30 to +55°C
Storage Temperature: -40 to +85°C
Humidity: 0 to 95% non-condensing
Altitude: Operating: -200 to +13,000ft

MECHANICAL

Size: 19" x 1.75" x 15.1" (483 x 44.5 x 384mm)
Weight: 17.5lb (8kg) (estimated)
Vibration: Operating: The unit will operate normally when subjected to Test 3 - Office Vibration Test Method of MIL-STD-883C, Paragraph 5.5.9 using the alternate test procedure.
Connections: Terminal blocks for input and output power

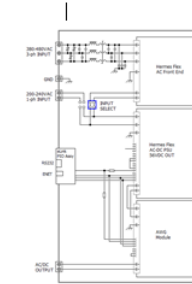
AGENCY COMPLIANCE

EMC: Conducted emissions meet FCC Part 15, Subpart A Class A, and EN55022, Class A on input power lines.
Isolation: Input to Output: 4000Vrms
 Input to Ground: 1625Vrms
 Output to Ground: 1000Vrms

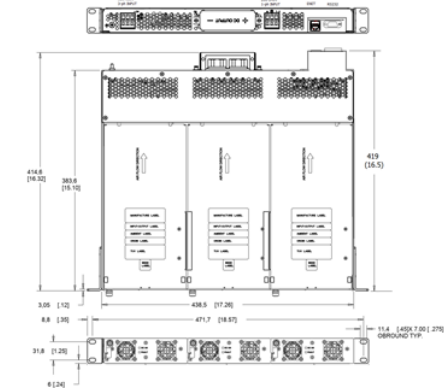
SAFETY:

UL/IEC/EN 61010-1 (pending)

Block Diagram:



Outline Drawing:



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