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Pulse-pulse repeatability in high-voltage capacitor charging power supplies

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Outline

- High voltage capacitor charging power supplies
- Pulse-to-pulse repeatability & factors affecting
- Reason for pulse-to-pulse voltage variation
- P-P repeatability under varying output voltage at constant repetition rate
- P-P repeatability under varying repetition rate
- CC, CP and CP-adaptive frequency control mode to achieve high P-P repeatability
- Energy absorbing circuit to achieve highest P-P repeatability

High Voltage Capacitor charging power supply

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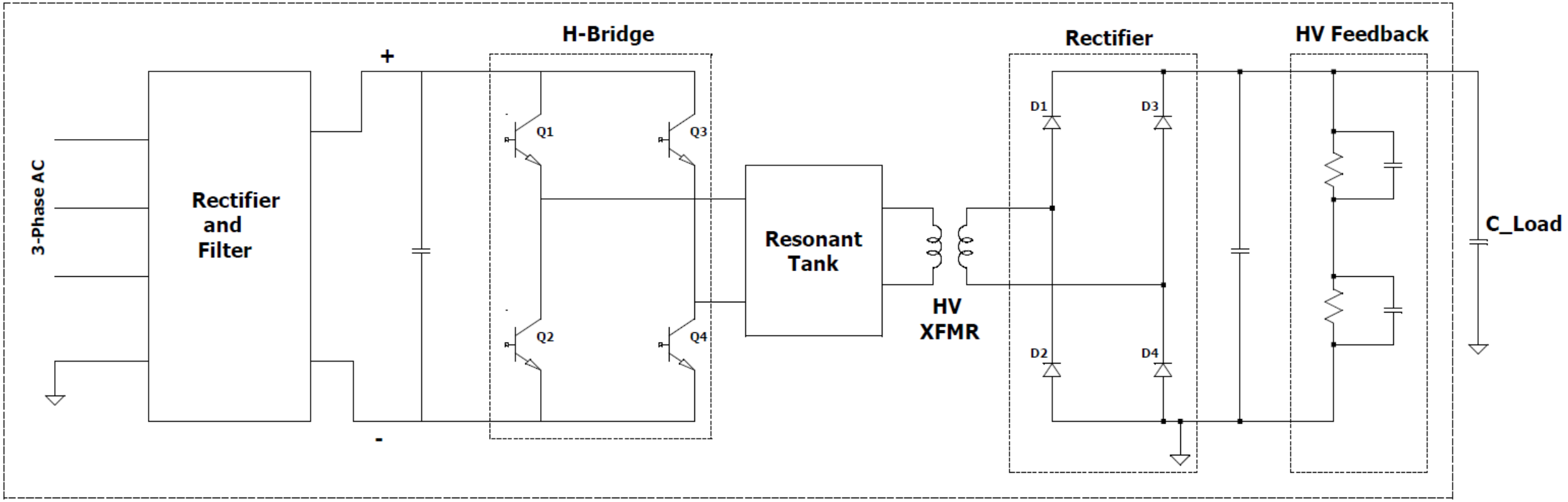

- A typical capacitor charging power supply uses a resonant topology with constant current characteristics.
- High voltage transformer parasitic components can be part of the resonant network.

High Voltage Capacitor charging power supply

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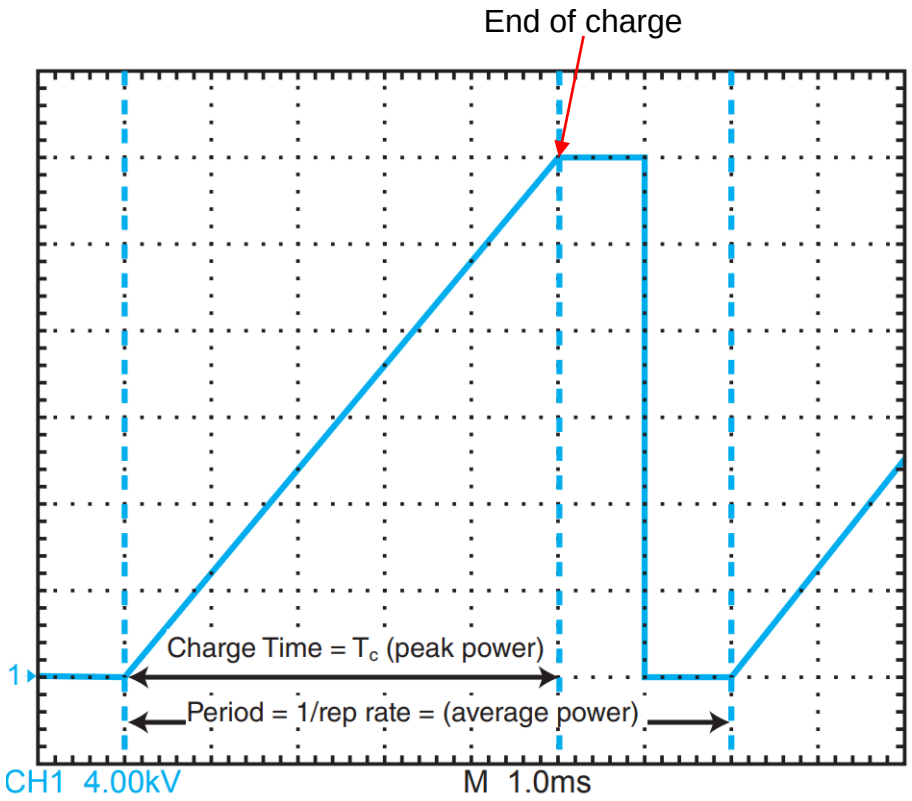
- Important specifications
  - Average and Peak Power Rating
  - Output voltage rating and polarity
  - Pulse repetition rate
  - Pulse to pulse repeatability
- CCPS Applications
  - High voltage pulse generators
  - Flashlamp drivers
  - X-ray imaging
  - Semiconductor testing
  - Pulsed plasma thruster
  - Accelerators



Typical CCPS output waveform

Capacitor charging power supply topologies

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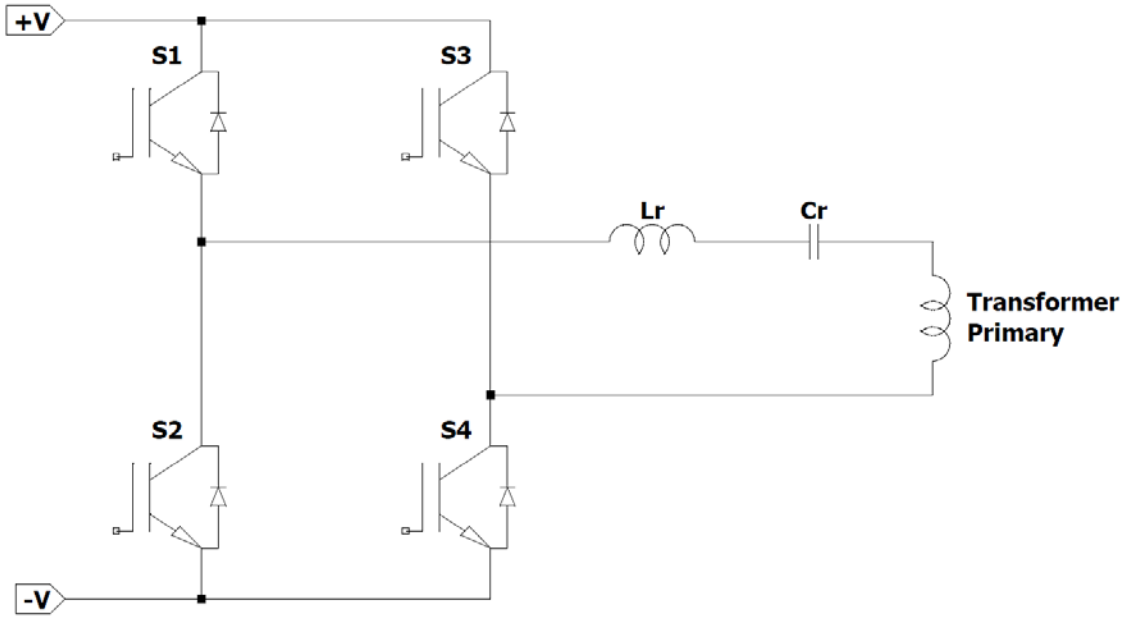
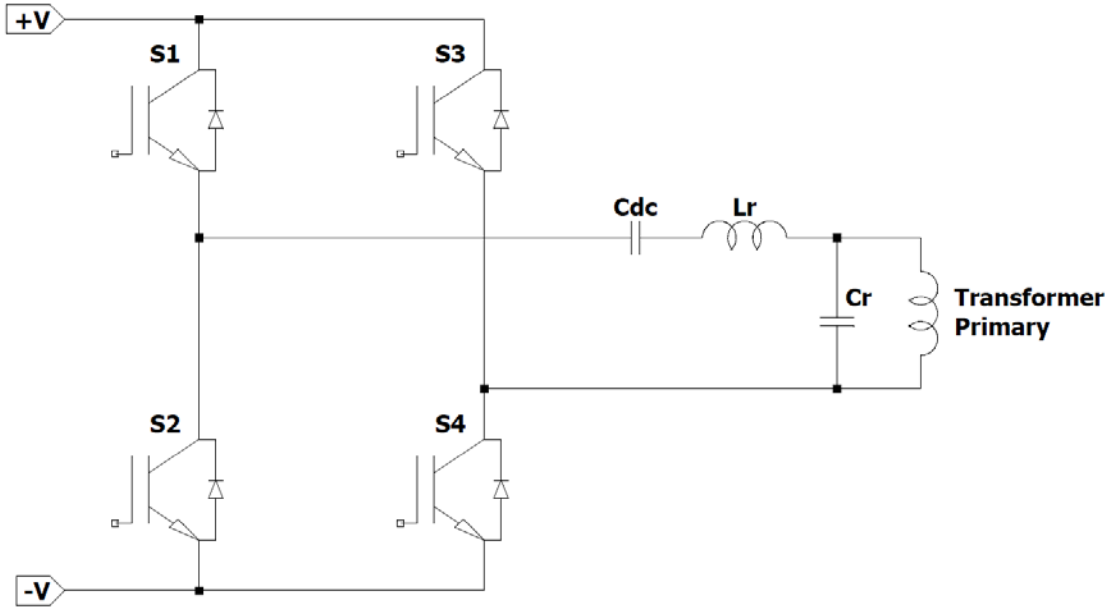
- Series resonant topology
  - Simple to implement
  - Low component stress
  - Soft switching capability
  - Only two resonant elements
  - Better pulse-pulse repeatability for large loads
  - Leakage inductance of HV transformer absorbed into Lr
  - Poor no-load regulation
  - Not inherently short-circuit proof
  - Large frequency variation for control



Series resonant topology

Capacitor charging power supply topologies

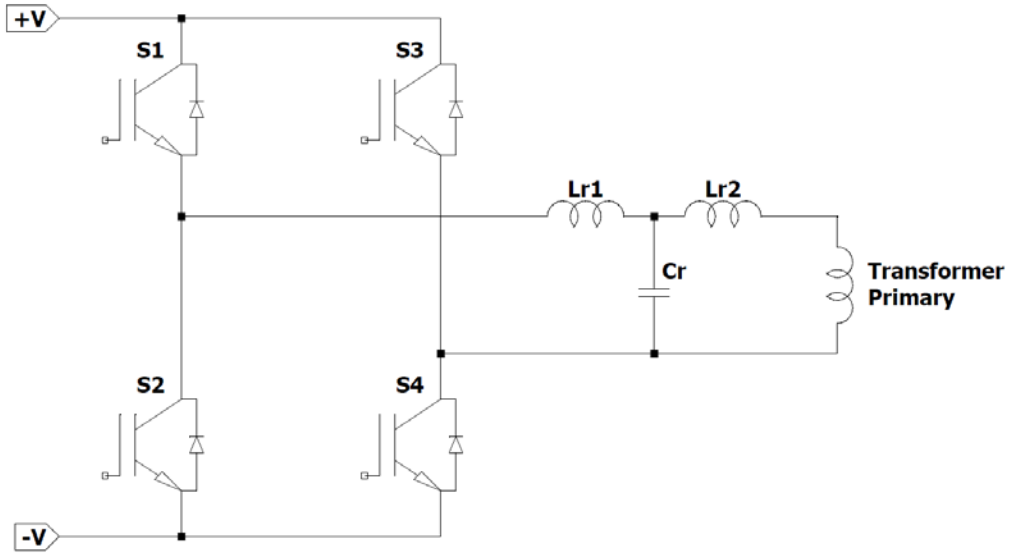
- Parallel resonant topology
  - Only two resonant elements
  - Inherent short circuit protection
  - Transformer parasitic components can be absorbed into the resonant network
  - Pulse-pulse repeatability up to 0.1% can be achieved
  - Poor part-load efficiency
  - Repetition rate limited due to energy stored in the resonant components



Parallel resonant topology

Capacitor charging power supply topologies

- LCL-T resonant topology
  - Constant frequency of operation
  - Phase shifted full bridge
  - Better pulse-pulse repeatability
  - Multiple resonant elements
  - No inherent DC blocking



LCL-T resonant topology

Pulse to pulse repeatability

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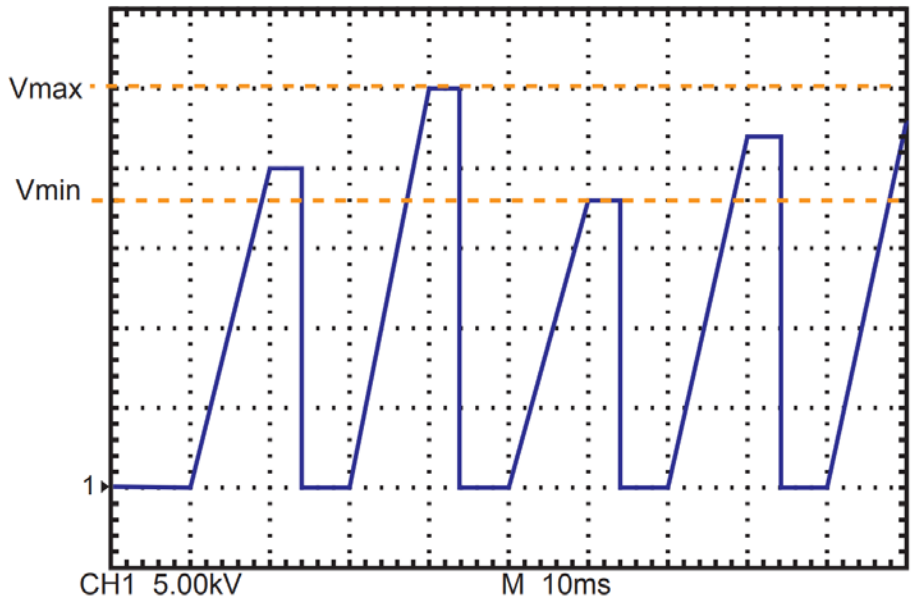
- Repeatability measures a power supply's ability to charge a load capacitor to the same voltage from one charge cycle to the next.
- Repeatability is expressed as a percentage variation of end of charge voltage, relative to the rated output voltage of the power supply.
- High-performance applications requiring high P-P repeatability include –
  - Excimer lasers
  - High energy X-ray
  - Radar



Typical CCPS output waveform

$$\%Repeatability = \frac{Vmax - Vmin}{Vrated} * 100$$

Factors affecting pulse-pulse repeatability

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- The following factors affect pulse-pulse repeatability
  - Accuracy of the voltage reference signal
  - Noise in the End Of Charge (EOC) signal
  - Delay from the EOC signal to the inverter turn-off
  - Energy stored in the resonant components at EOC
  - Load capacitor
  - Repetition rate
  - Output voltage
  - Switching frequency

Factors affecting pulse-pulse repeatability

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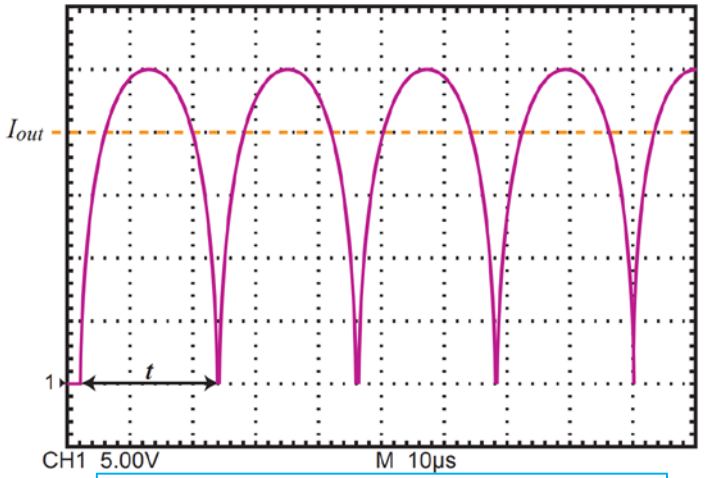
Output current, switching frequency, and load cap

- The current output from the supply is formed by multiple consecutive charge ‘buckets’.
- The size of the charge buckets is determined by the output current rating and the switching frequency of the power supply.
- Every charge bucket delivered to the load raises the potential on the load capacitor by a small voltage ‘ΔV’.
- The voltage step (ΔV) depends on the load capacitor value as shown in the equation.



Typical output current waveform

$$\Delta V = \frac{I_{out} * t}{C_{load}}$$

ΔV = voltage variation from one pulse to the next
t = half of the inverter switching period
I_{out} = Average output current
C_{load} = Load capacitor

Factors affecting pulse-pulse repeatability

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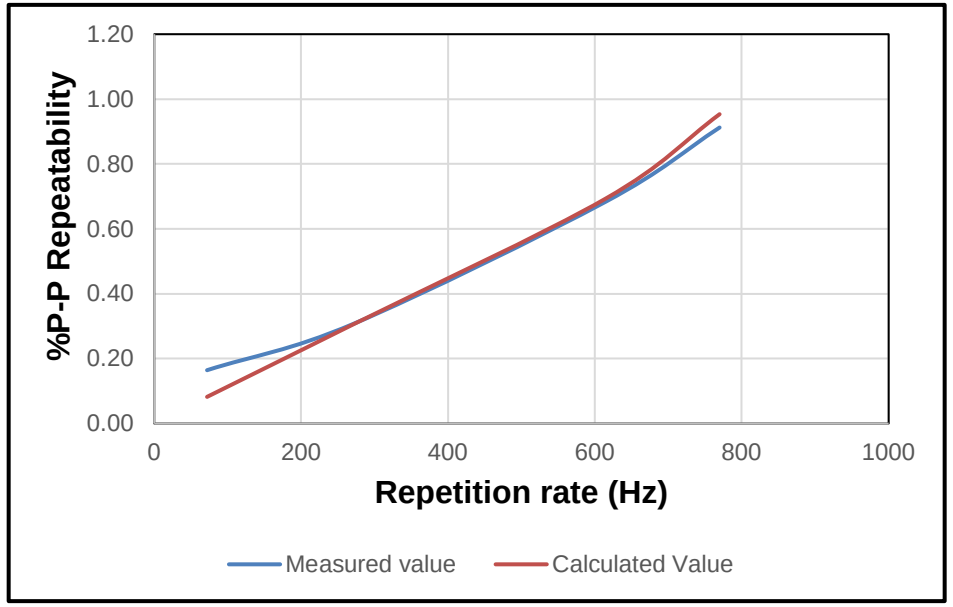
Repetition rate

- With a higher repetition rate, the load capacitor is small, assuming the total power delivered / power supply max output is constant.
- With the load capacitor being small, pulse-to-pulse repeatability is higher for the same charge bucket.
- The graph on the right shows pulse to pulse repeatability for a standard TDK 802 capacitor charging power supply.



Pulse-to-pulse repeatability vs. output rep rate

Factors affecting pulse-pulse repeatability

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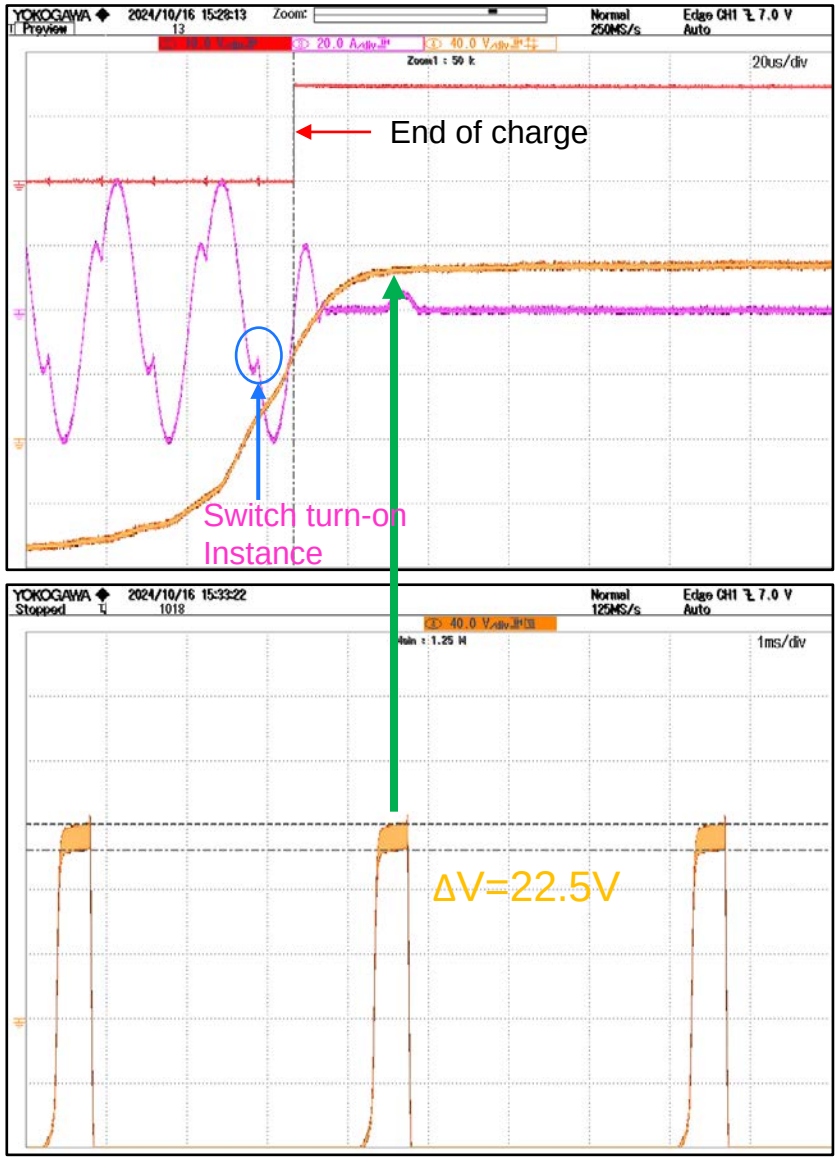
Output voltage

- High pulse-pulse repeatability is achieved when end of charge occurs away from the device turn-on instance in the full bridge inverter.
- Top waveform shows the end of charge signal with respect to the inverter device switching instance.
- Bottom waveform shows pulse-pulse repeatability over 3000 pulses.
- This data corresponds to the TDK-Lambda 802 power supply series.



Factors affecting pulse-pulse repeatability

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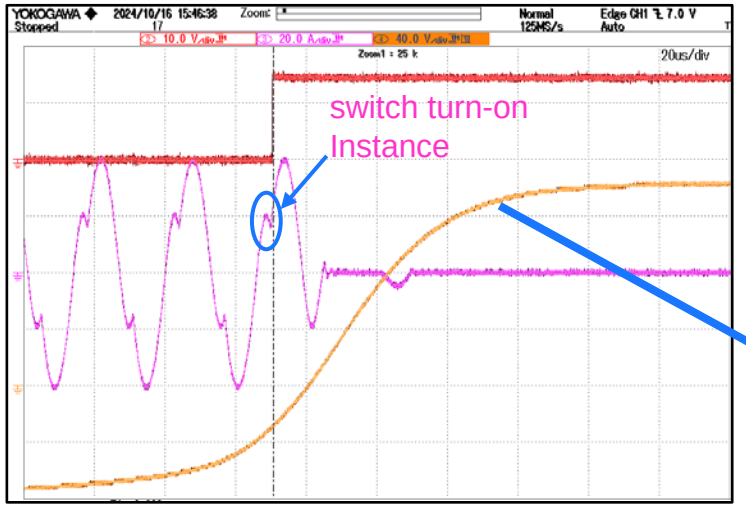
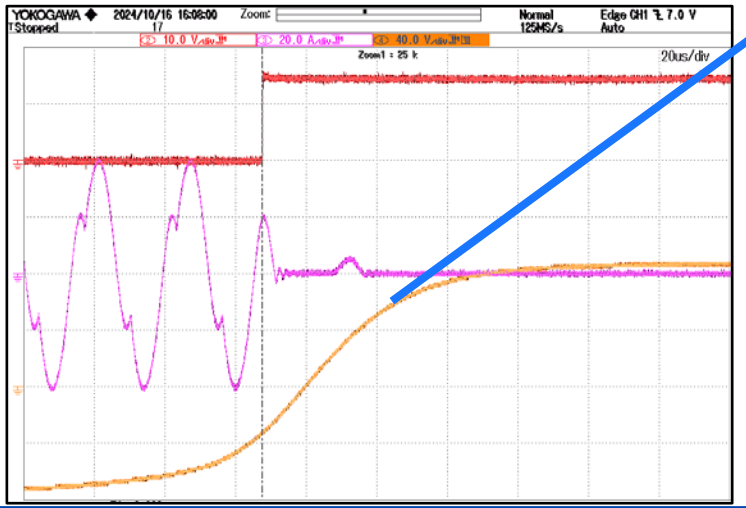
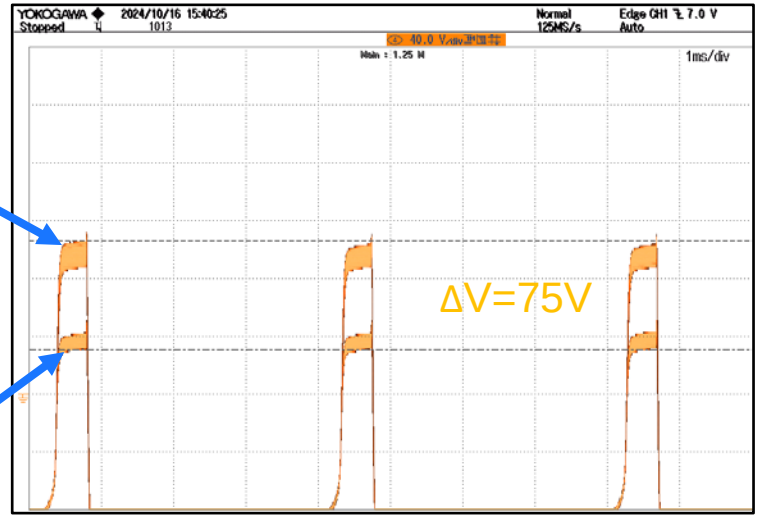
Output voltage

- Poor pulse-pulse repeatability due to end of charge occurring close to the inverter switch turn-on instance.
- Top waveform shows EOC occurring right after the switch turn-on instance.
- Bottom waveform shows EOC occurring right before the switch turn-on instance.
- Waveform on right-hand side shows variation in output voltage at the end of charge over the period of 3000 pulses.







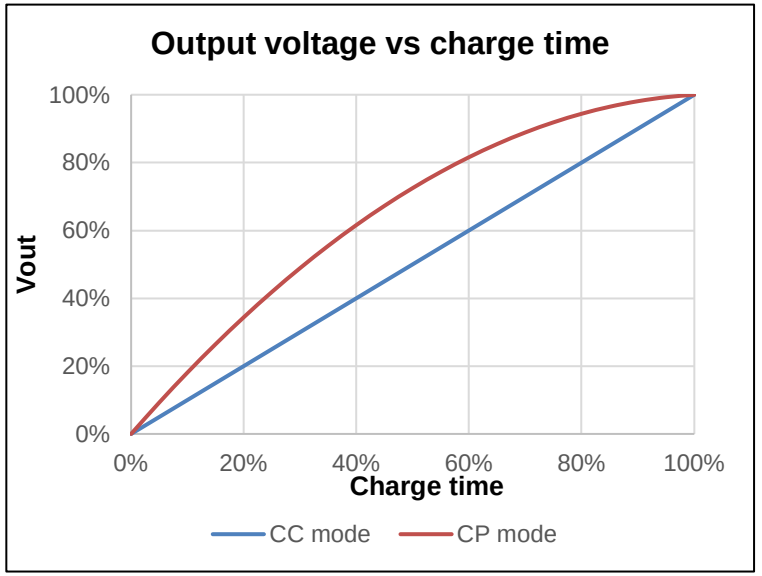
Pulse-pulse repeatability Improvement techniques

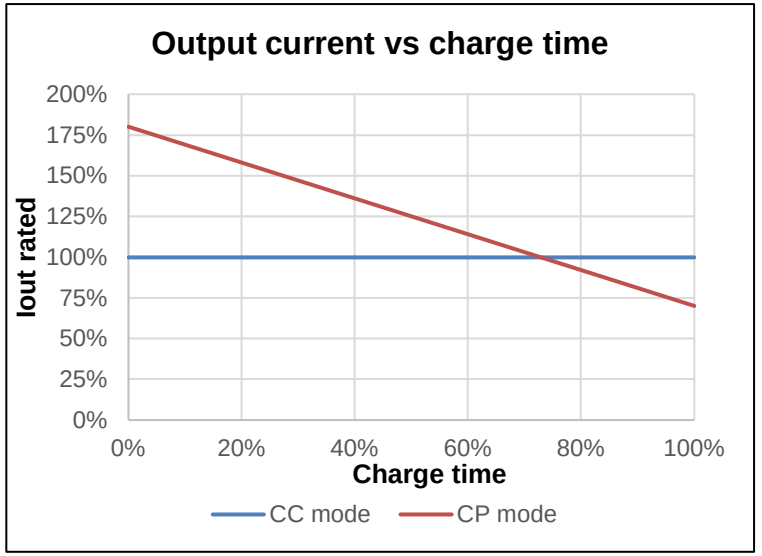
- Following techniques can be implemented to improve P-P repeatability
  - Constant power mode operation
  - Constant power mode with adaptive frequency control
  - Energy absorption circuit

Pulse-pulse repeatability Improvement techniques

Constant power mode operation

- Power supply operation in quasi-constant power mode
  - CCPS provides almost twice the rated current at the beginning of the charge and approximately 70% of the rated current towards the end of the charge.
  - This helps in achieving high P-P repeatability due to smaller charge bucket size towards the end of charge.
  - Higher component stress and peak power to compensate for the lower output current towards the EOC.

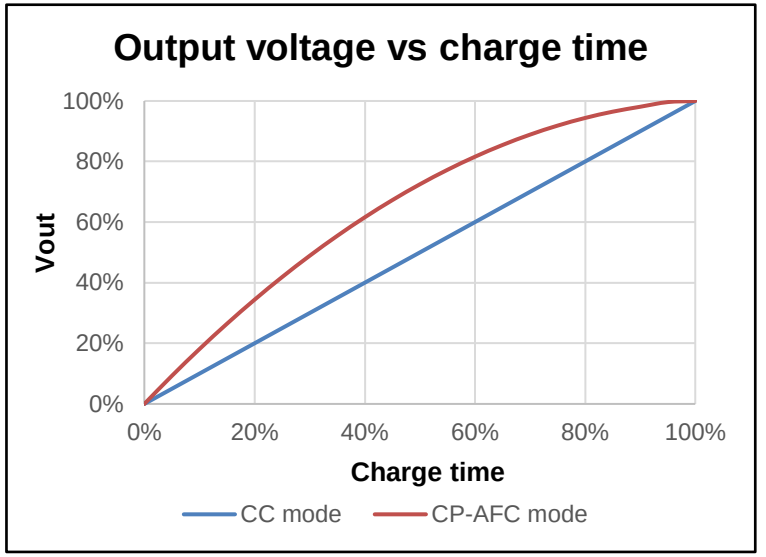


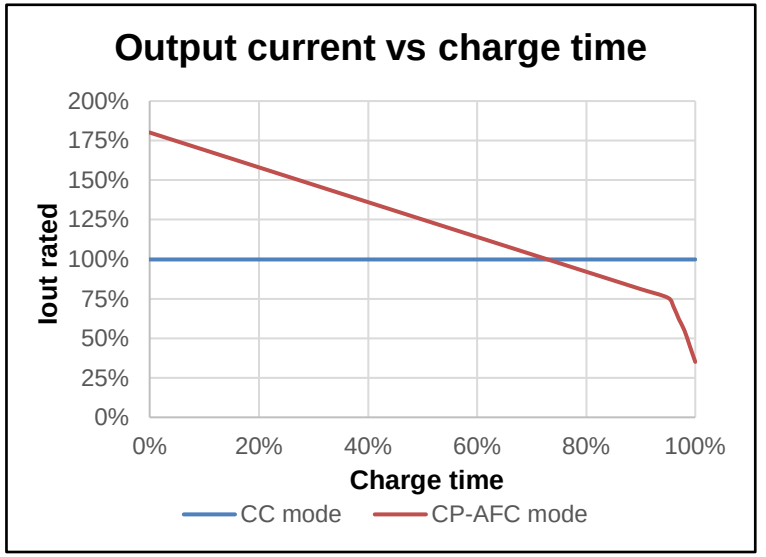


Pulse-pulse repeatability improvement techniques

Constant power mode with adaptive frequency control

- Adaptive control of converter switching frequency
  - Switching frequency is controlled to achieve the desired current gain for 90-95% of the charge cycle.
  - For the last 5-10% of the charge cycle, the switching frequency is adjusted to decrease the current output.
  - Higher component stress and peak power to compensate for the lower output current towards the EOC.

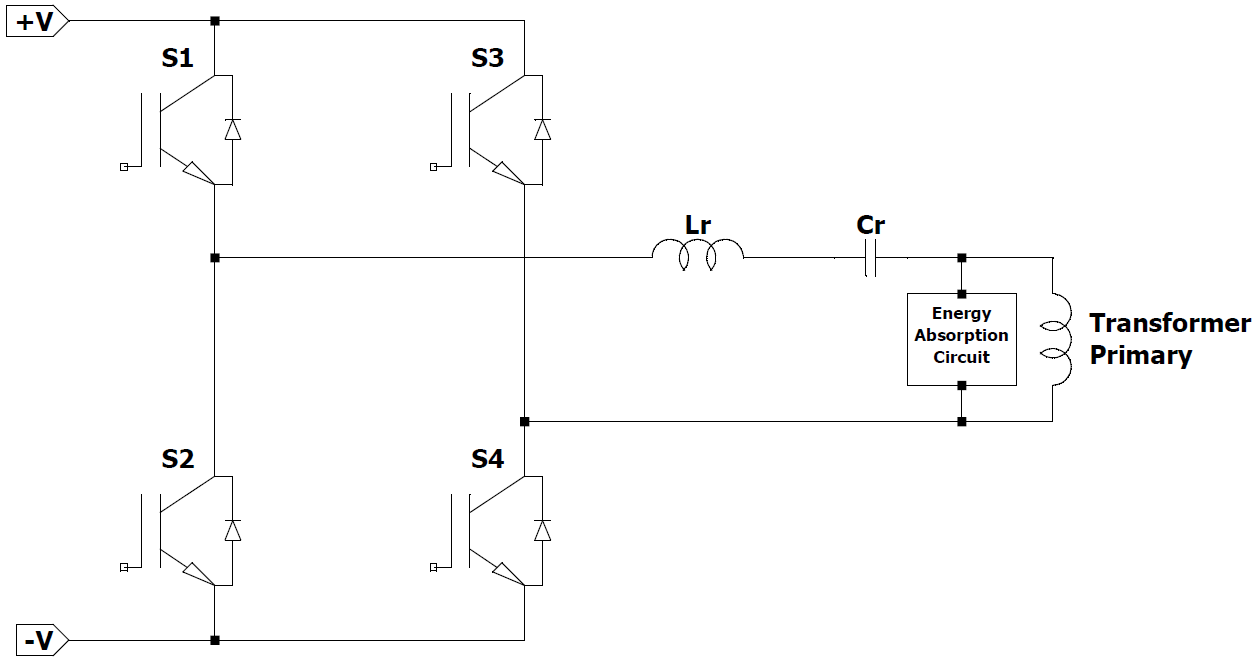




Pulse-pulse repeatability improvement techniques

Energy absorption circuit

- Energy absorption circuit
  - Stored energy in the resonant network is dissipated in the energy absorption circuit instead of transferring to the load capacitor after the EOC is detected.
  - Additional circuitry for detection and implementation and increased component count.

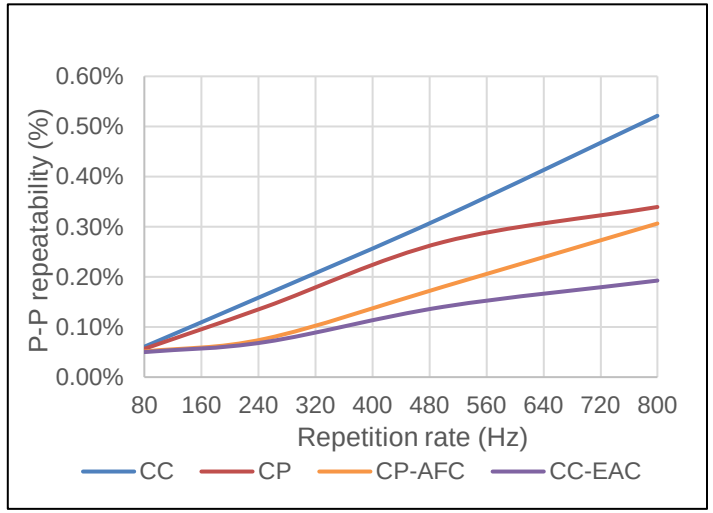


Series resonant topology with energy absorption circuit

Pulse-pulse repeatability improvement techniques

CC, CP, CP-AFC, CC-EAC comparison

- CP-AFC operation advantages
  - No additional components required
  - Simple to implement
- CP-AFC operation drawbacks
  - Higher inverter RMS current
- CC-EAC operation advantages
  - Less than +/-0.2% pulse-pulse repeatability at repetition rates up 1kHz can be achieved
- CC-EAC operation drawbacks
  - Additional components and control circuits



Pulse-to-pulse repeatability comparison with various techniques

TDK-Lambda HV capacitor charging product lines

- Rack mount capacitor charging and DC power supplies
  - Products ranging from 1kV up to 50kV
  - Some models can be configured as continuous DC power supply
  - Power supplies can be connected in parallel to achieve higher power

202A (Shoebox)

HV out up to 40kV
PPR of 0.2%
PRR up to 300Hz

402/802

HV out up to 50kV
PPR of 2%
PRR up to 1kHz

LC1202

HV out up to 30kV
PPR of 0.1%
PRR up to 300Hz

303

HV out up to 50kV
PPR of 2%
PRR up to 100Hz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