Design of an 80kV, 40A Resonant SMPS for Pulsed Power Applications

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IEEE IPMHVC June 4, 2012

Three Phase Resonant Power Supply

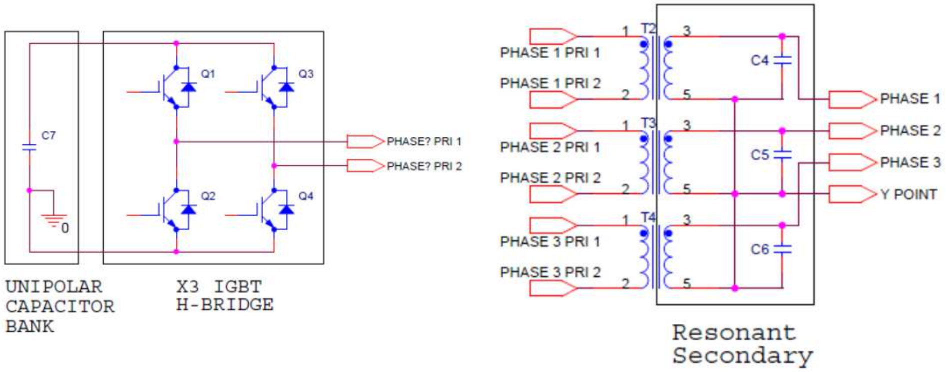
Designed to power a klystron tube

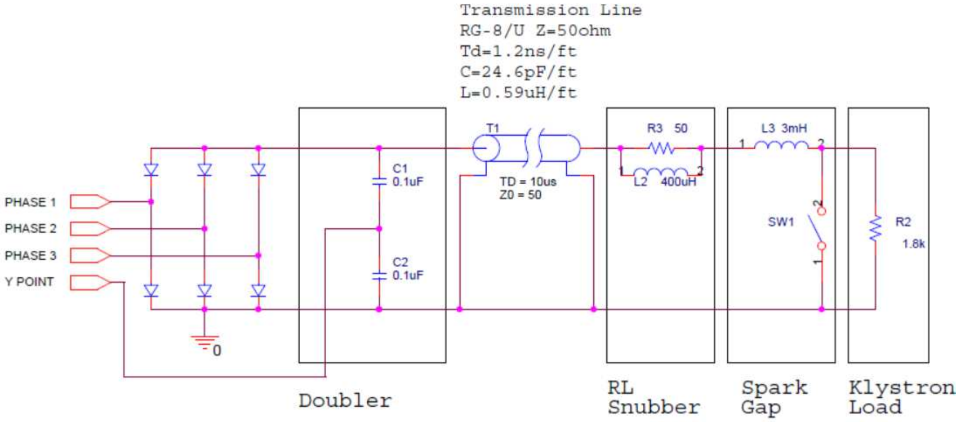
Power Supply Specifications

- Klystron tube requires -75kV to -80kV, 36A to 40A for 10ms
- Maximum output 95kV, 53A (5MW)
- Fast rise time (~0.3ms)
- Low stored energy in filters
- Low voltage ripple
- Tolerant of load arcs
- Feedback control to compensate for capacitor bank voltage droop

Three Phase Resonant Power Supply

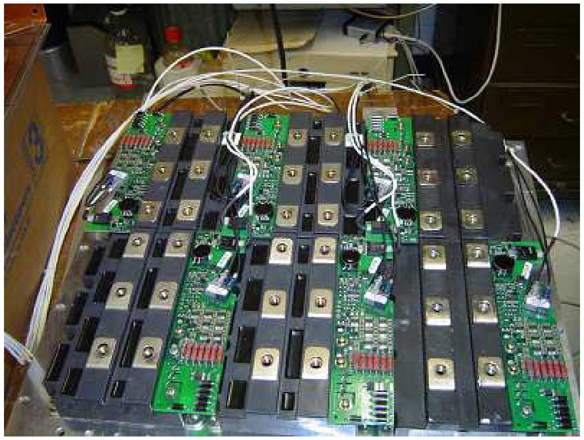
- Electrolytic capacitor bank:
  - 900V, 0.3F
- Full H-bridge per transformer
- Transformers have loosely coupled secondaries, parallel LC resonance
- 3 phase doubling configuration
  - Secondaries connected in Y
  - Y point connected to center of doubler capacitor
- RL snubber at the end of transmission line
- Crowbar sparkgap
- dsPIC microcontroller control system

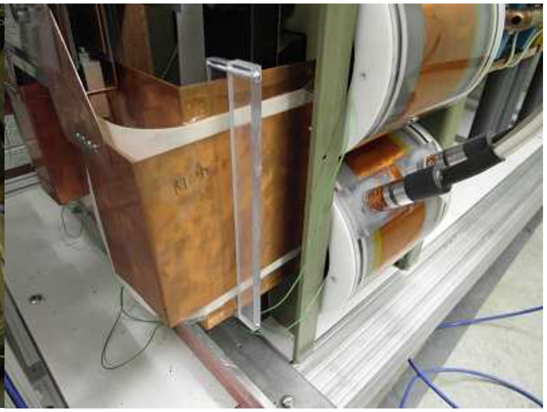


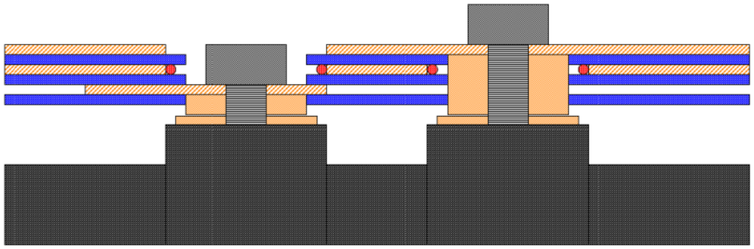


IGBT H-bridges and Gate Drivers

- Full H-bridge per transformer
- IGBTs: 3.3kV, 1.2kA (CM1200HB-66H)
- CT concepts plug and play gate drivers
  - Isolated from dc power supply
  - Fiber optic control
- Low inductance bus plates
  - 1/16” copper plates with 1/16” polycarbonate insulation
  - Low ESL stiffening capacitors

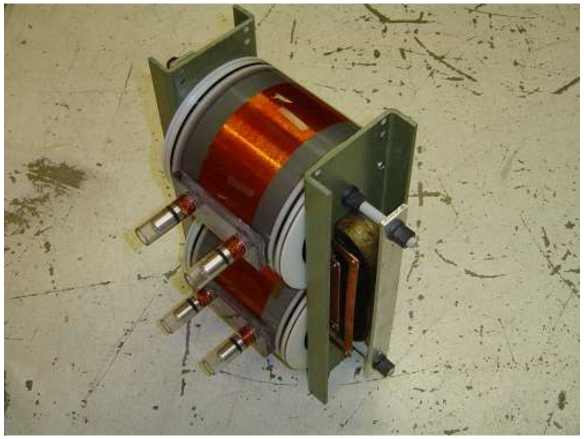


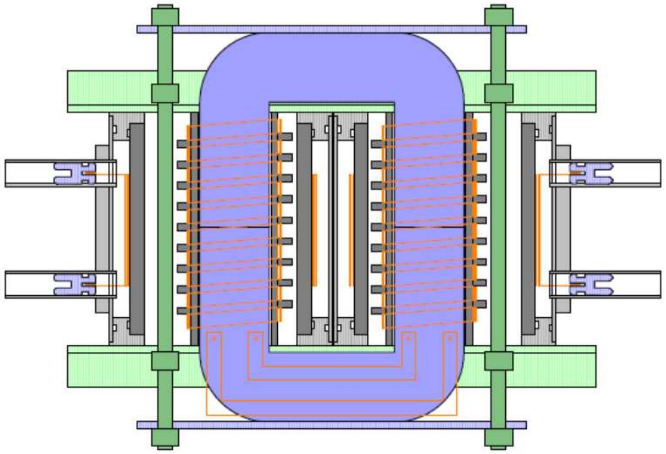


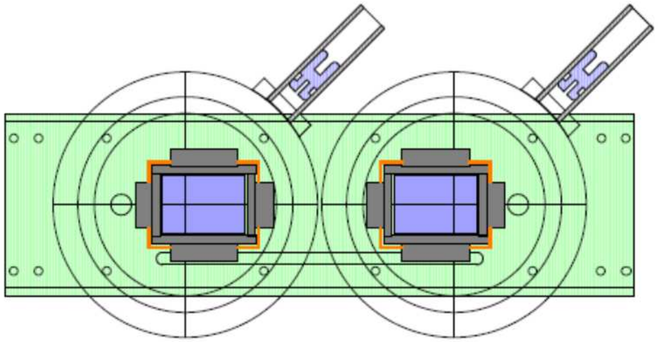


Resonant Transformer Design

- Nano-crystalline iron core
- Loosely coupled secondary for high leakage inductance
- Parallel resonator capacitance 0.05uF
- Secondary leakage inductance 1.36mH
- 136 turn secondary
- 10 turn primary
- 120:1 boost ratio at resonance
- Oil immersed secondary for insulation and corona prevention

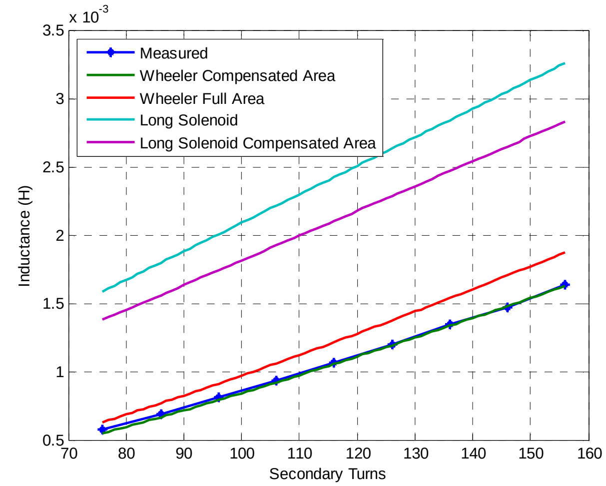






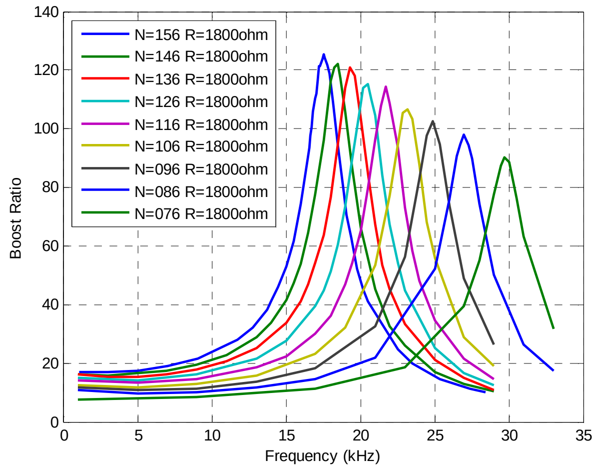
Resonant Transformer Model

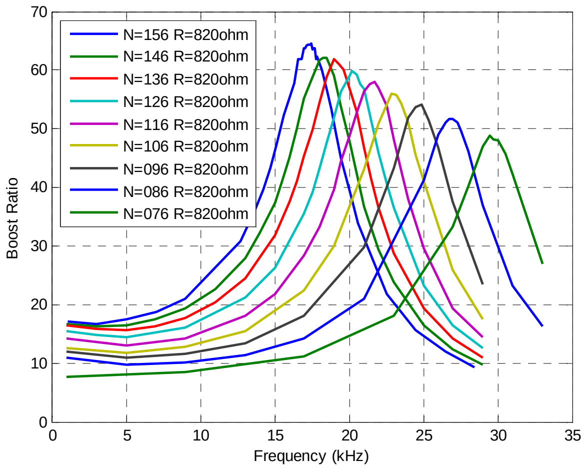
- Mathematical model of leakage inductance to avoid trial and error transformer design
  - Use Wheeler's formula for a short solenoid
  - Assume magnetic flux is excluded from core when primary is shorted
  - Modify for leakage inductance by subtracting core area from coil cross section area



$$L_{long} = \frac{\mu_0 N^2 A}{h_{coil}}$$

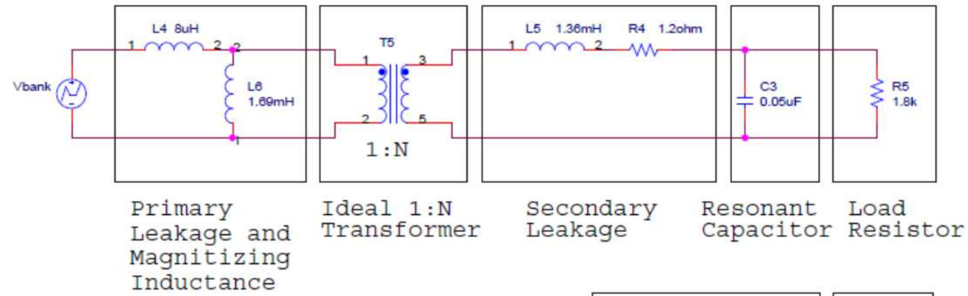
$$L_{wheeler} = \frac{10\mu_0 N^2 \left(A - A_{core}\right)}{\left(9r_{coil} + 10h_{coil}\right)}$$





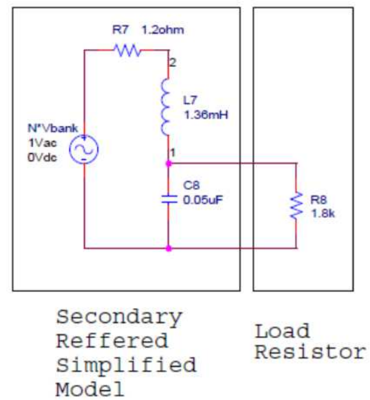
Resonant Transformer Model

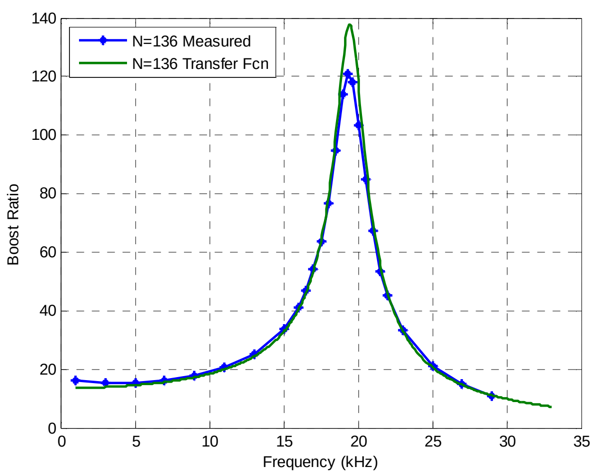
- Model of transformer boost ratio frequency response
- Transfer function from simplified secondary referred model
- Accurate prediction of resonant frequency and measured transfer function

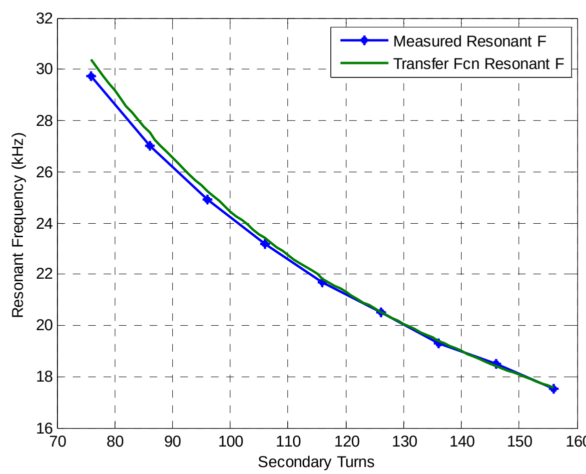


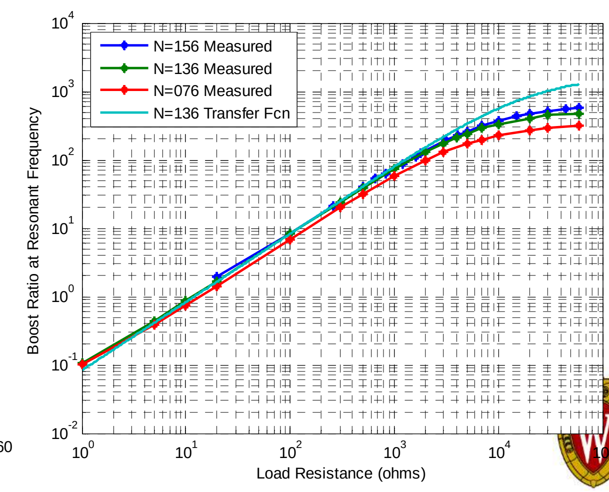
$$\frac{V_{sec}}{V_{pri}} = \frac{N}{\left[1+\left(R_{inductor} + j\omega L\right)\left(\frac{1}{R_{load}} + j\omega C\right)\right]}$$

$$F_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} + \frac{1}{(RC)^2}}$$



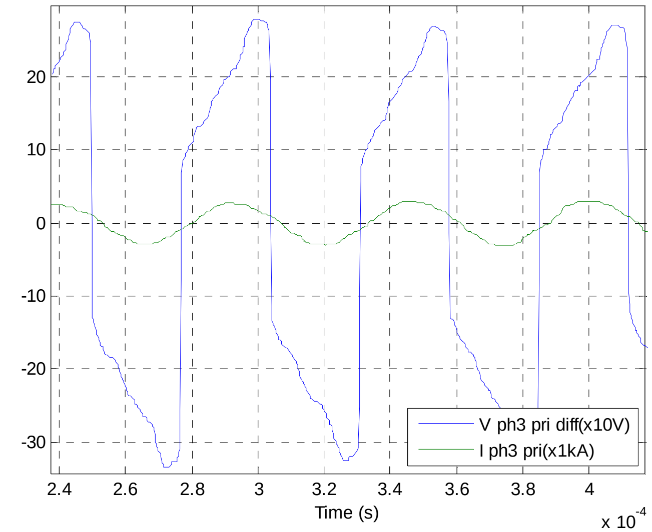




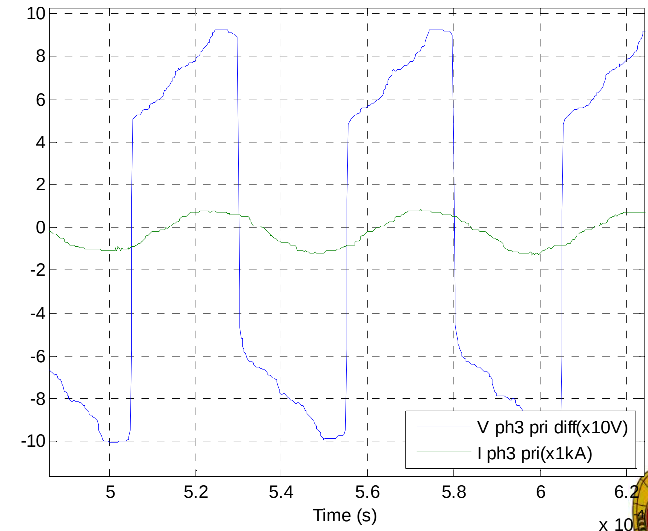


Resonant Transformer Primary Waveforms

- Soft switching at resonance (ZCS)
- 18.5khz
  - Switching near zero current



- 20khz
  - Switching moves away from zero current

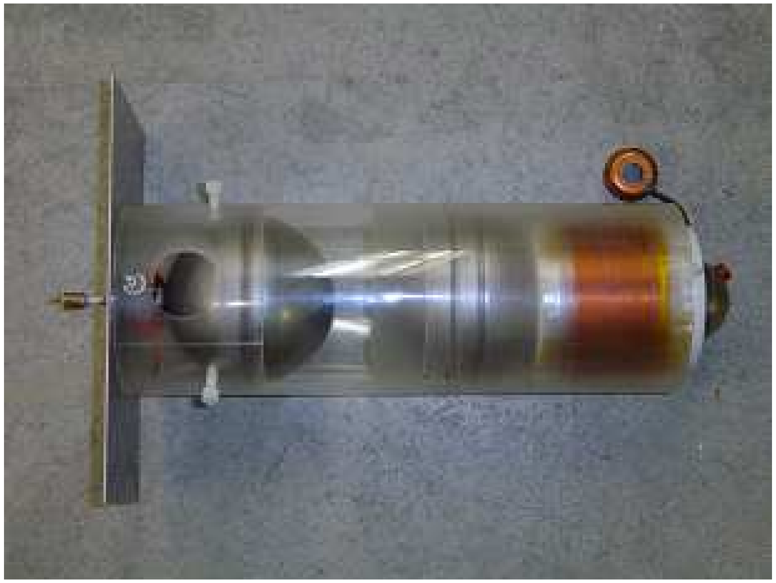


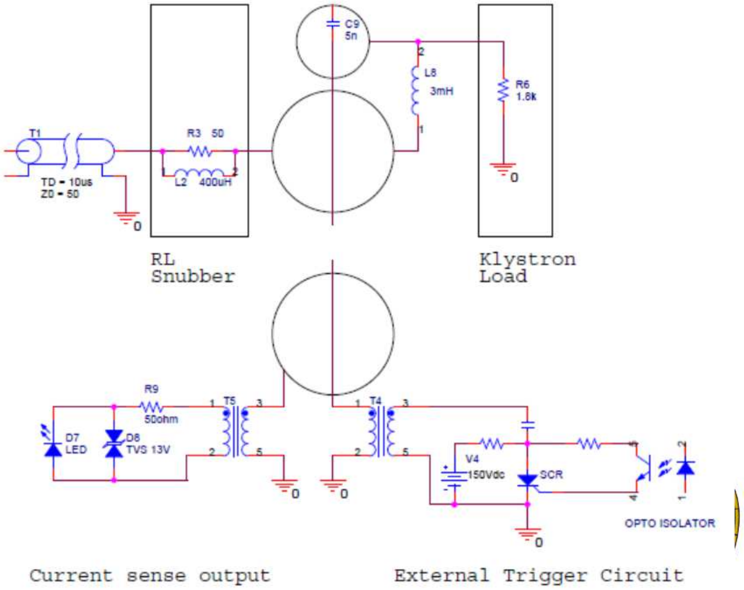
Crowbar Sparkgap

- In the event of an internal arc, damage to the klystron's cathode may occur
- 140J stored in doubler capacitors at 75kV
- Spark gap crowbars voltage across klystron tube in the event of arc.

- Methods of triggering
  - Overvoltage: Gap spacing
  - di/dt: series inductor connected to top trigger electrode
  - External trigger: connected to klystron RF detector

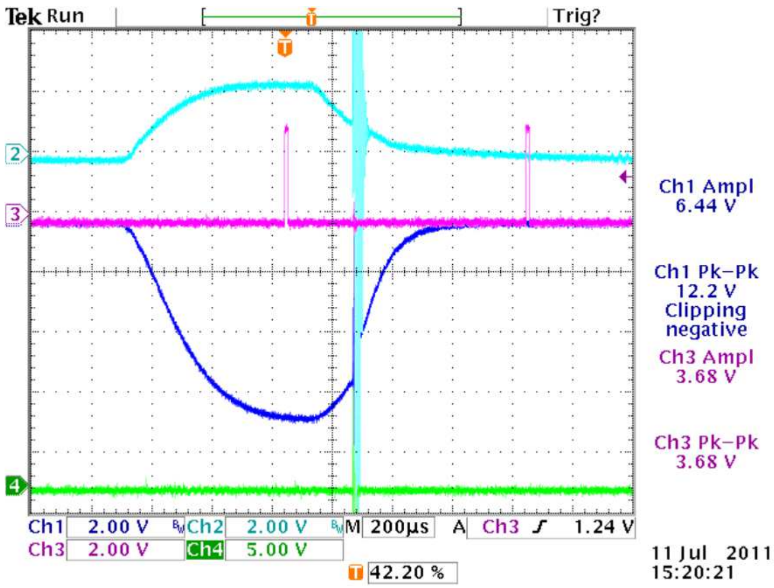
- Current sense output: shutdown signal to power supply if sparkgap fires.

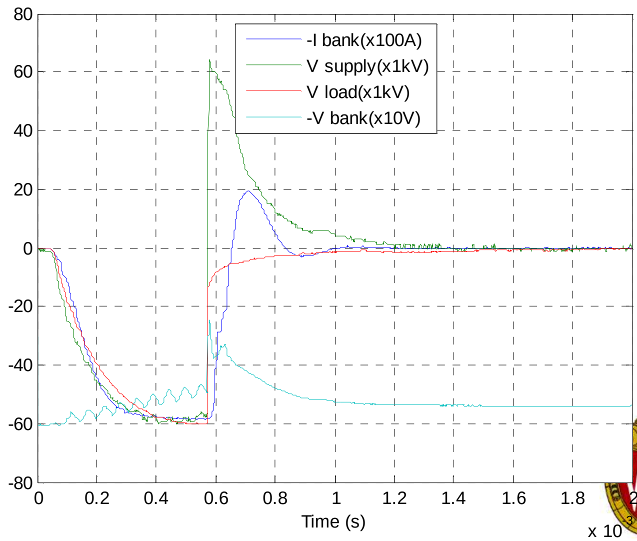




RL Snubber

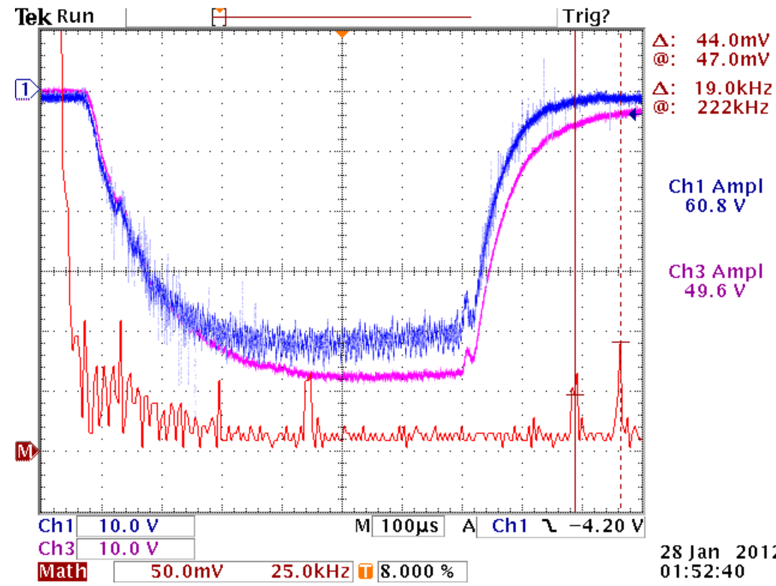
- Klystron arc generates HV pulse and ringing on transmission line
- Damage to doubling capacitors
- RL snubber added
  - R=50ohm, L=400uH
  - Series connection with Klystron
  - Mounted inside insulating PVC pipe
- Elimination of ringing, reduction of reflected pulse amplitude

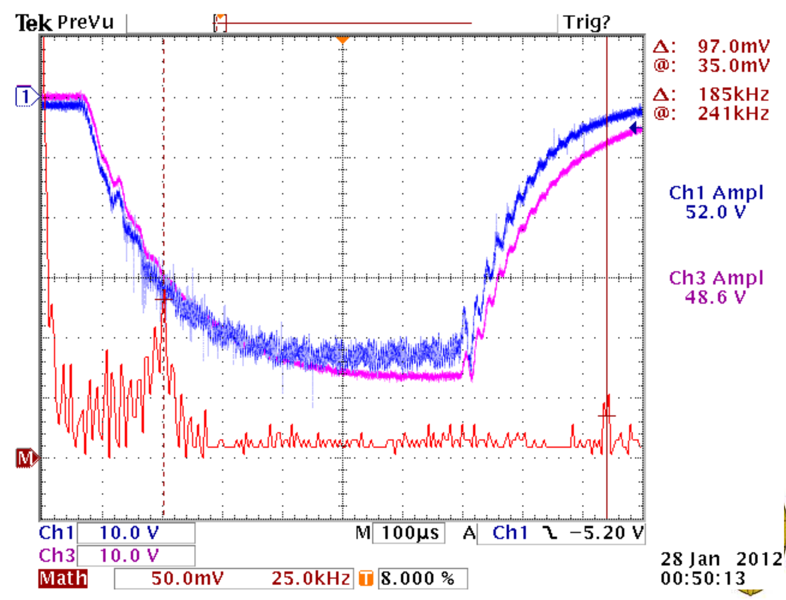




Harmonic Mitigation and Filtering

- Three phase rectifier
  - 6^{th} harmonic ripple
- Unbalanced secondary voltages
  - Variations in resonant frequency
  - Primarily 1^{st}, 2^{nd}, and 4^{th} harmonics
  - Trimming of PWM duty cycle
  - Trimming resonant frequency by adding external inductance
- Lowpass Pi filter
- LC harmonic filter tuned to 6^{th} harmonic

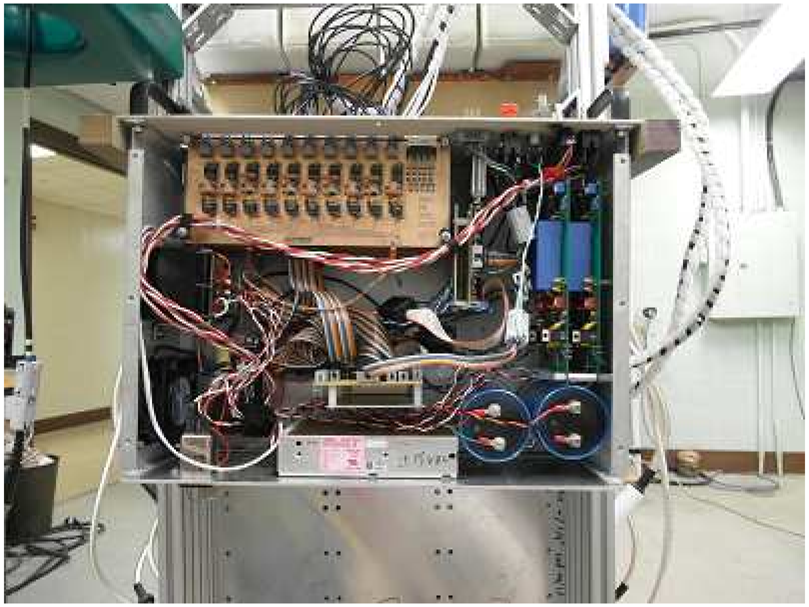


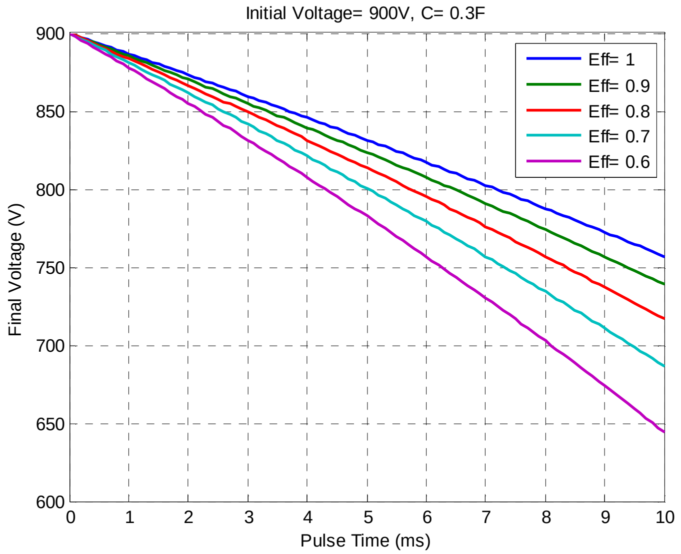


Control System

- Microchip dsPIC30F2020 microcontroller
  - Designed for SMPS use
  - 30 MIPS operation
  - High speed ADC (10bit, 2msps)
  - Time base synchronized PWM allows constant phase separation of primary waveforms
  - 120 control loop cycles per ms
- Fiber optic control of IGBT modules
- Ground loop isolated inputs

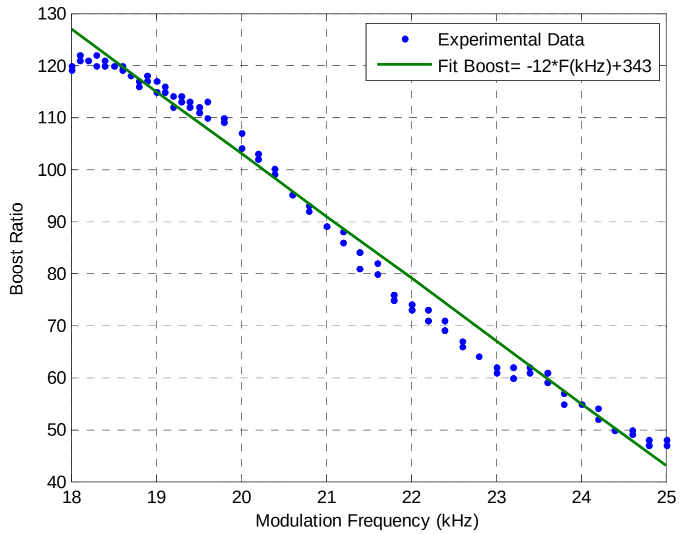
- Feedback/feedforward methods
  - Capacitor bank voltage: Operational
  - Output voltage: Development in progress

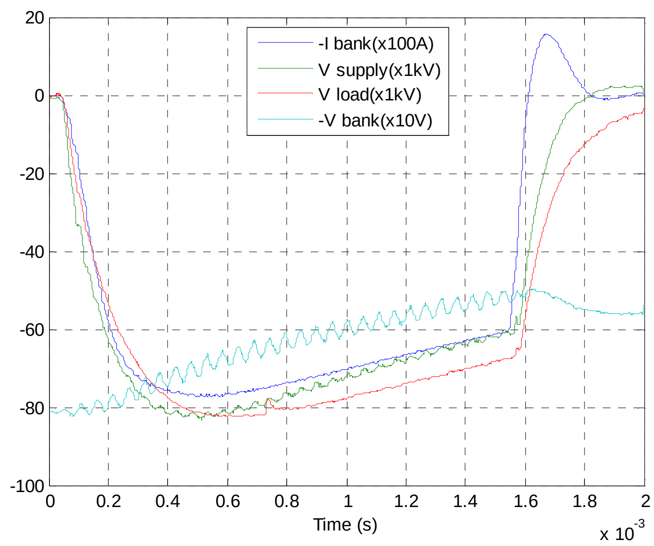


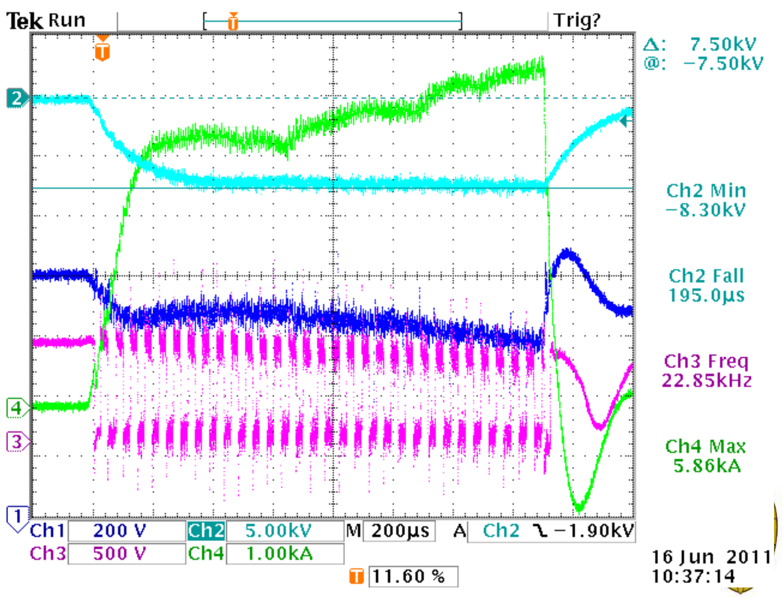


Control System

- Controller tunes switching frequency toward resonance to compensates for capacitor bank droop to stabilize output voltage
- Linearized approximation of boost ratio vs frequency
- Boost(Fkhz)=-12*Fkhz+343







Questions?

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Scan me for email address.