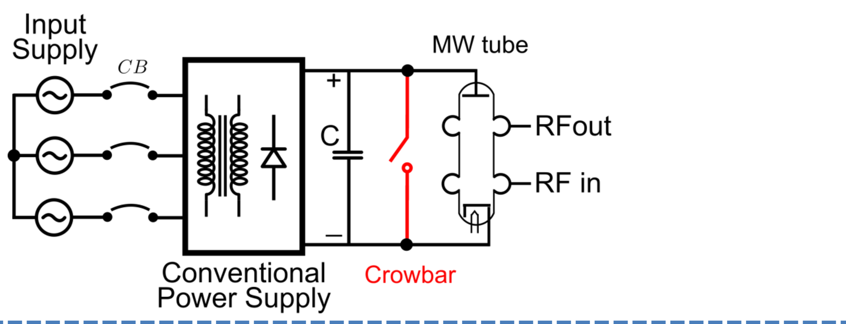
HIGH VOLTAGE POWER SUPPLY AND CROWBAR PROTECTION

Subhash Joshi T G, CDAC, Trivandrum Vinod John, IISc, Bangalore

EECS Research Students Symposium 2017

Solid state crowbar (SSC)

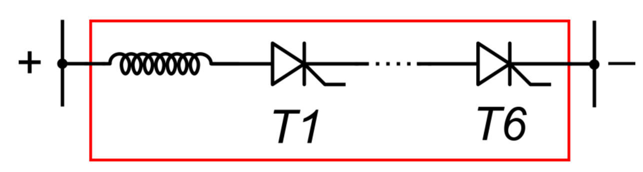
- Crowbar is a pulse power switch
- Microwave tube (MWT) is a load to many applications
- Maximum energy tolerable by MWT in the event of a fault
  - Specified by the manufacturer below 10J
  - Limiting the energy within this value MWT restores MWT to healthy condition
- Solid State Crowbar used as protective device to MWT
  - Connected in parallel to MWT and provides an easiest path for energy to flow
  - Limit the energy into the MW tubes within the specified value



Literature of Crowbar

- Commonly used switches are
  - Ignitron, thyratron [1-3]
    - mercury gas filled tube
    - use of these devices is restricted now a days
  - spark gap [4]
    - nitrogen gas filled device
    - frequent inspection and maintenance

- State of art is to use semiconductor devices [5]
  - Thyristors are used as semiconductor switch



- SSC of 10kV dc, 1kA peak current and 10MW peak power
- Should transfer energy in 10µs

1. Contributions for modelling

- **Model of fault current:**
- To match the ***Joules Integral (J.I.)*** due to the current instead matching the actual waveform

$$J.I. = \int i_d^2(t)dt$$

- Fault current is due to the current from input supply and due to the discharge of output capacitor,

$$i_d(t) = I_{d,avg.}\left[1 - e^{-\delta t}\left(\cos\omega_d t + \frac{\delta}{\omega_d}\sin\omega_d t\right)\right] + \frac{V_{C,init}}{R_1}e^{-\frac{t}{\tau_1}}$$

- **Model of MW tube:**
- Internal arc event is modeled using a fuse wire
- Energy conservation relation for the fuse wire for an incremental time Δt

$$i_d^2(t)R(\sigma(T))\Delta t = Al\rho C_P \Delta T + d\psi_{conduction} + d\psi_{convection} + d\psi_{radiation}$$

- J.I. and temperature are related as

$$\int_0^t i_d^2(\tau)d\tau = \frac{A^2\rho C_P \sigma_o}{\alpha_o}\ln(1+\alpha_o(T-T_o))$$

1. Indian patent filed with number "201641025723 dated 27/07/2016" jointly by CDAC & IISc
2. T. G. Subhash Joshi and V. John, "Microwave Tube Fault-Current Model for Design of Crowbar Protection," in the Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES), 2016

2. Design of di/dt limiting inductor

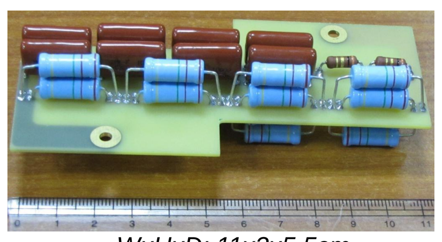
- Required to avoid local hot spot in the thyristor due to high di/dt
- Energy accumulation in the MW tube is increased by,
  - di/dt limiting inductor
  - Turn-on delay time of the thyristor
- Two boundary conditions of inductance are estimated from,
  - Expression relating inductance, energy in MW tube, and turn on delay time
  - Expression relating inductance and slope of current through thyristor (di/dt)

Inductance: 250µH
Voltage: 10kV dc
Peak current rating: 1kA
WxDia: 32x12cm

Indian patent filed with number "201641015749 dated 05/05/2016" jointly by CDAC & IISc

3. Voltage balancing network

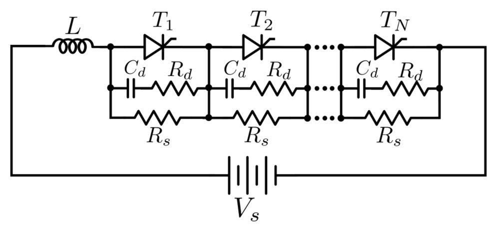
- Design based on difference in turn-on delay
- Component tolerances are considered
- Differences in propagation delays among thyristor drivers are incorporated
- Functionality without complex pulse synchronizing circuit
- Expressions for static and dynamic components



WxHxD: 11x3x5.5cm

$$V_{C_d,max} = \frac{V_s}{N} + \frac{V_s(N-1)}{Nt_{on}}\left[t_{dON} - \sqrt{L(1-a_C)C_d}\sin\left(\frac{t_{dON}}{\sqrt{L(1-a_C)C_d}}\right)\right] \quad ; \quad R_d C_d = t_{on}/50$$

Variable	Method	
	Proposed	Conventional
C_d	40nF	2250nF (56 times)
I_{max}	16A	900A (56 times)



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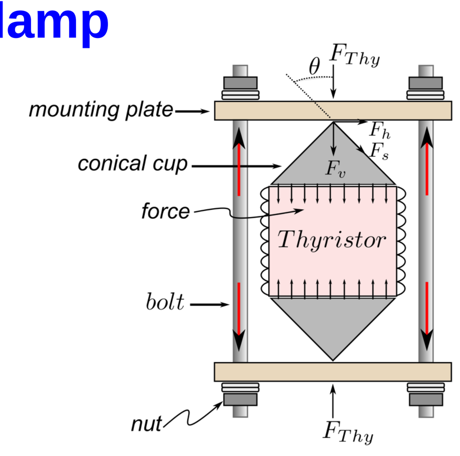
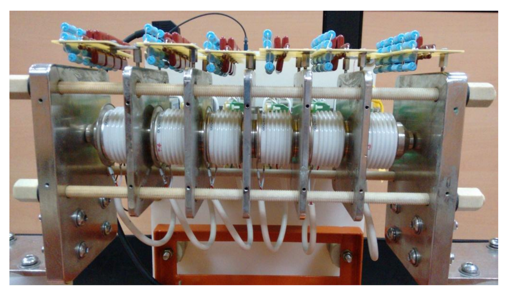
4. Mounting clamp

- Mounting force required for the desired electrical characteristic from the thyristor datasheet
- Design of mounting clamp involves:
  - Estimation of torque for the required force
  - Uniform force distribution over the pole face
  - Selection of bolt-nut and, design of mounting plate





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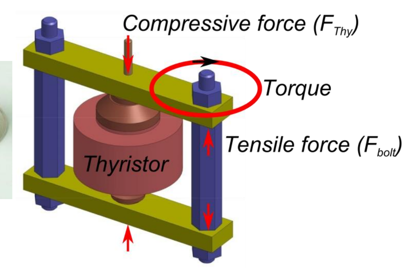

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5. Other contributions in SSC

- **Computation of combined transient thermal impedance (Z_{th}) of the system**
  - Z_{th} captures the temperature variation at any point for a step input power
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    - Thyristor , Heatsink: *can be estimated experimentally*
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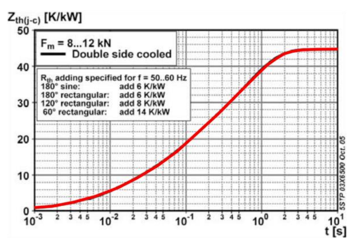


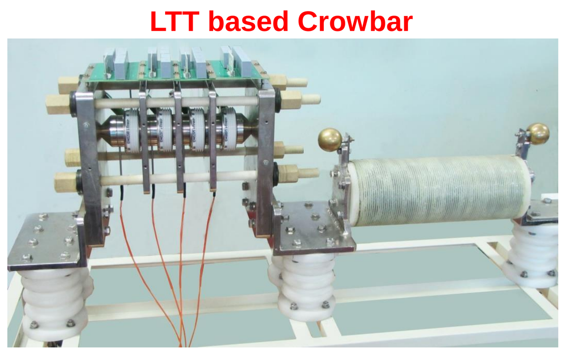
- **Selection of cable for the pulse power application**
  - High peak current flows for a short duration of time
    - Conventional method of selecting the cable by current density is inappropriate
  - Procedure considers:
    - ambient temperature
    - temperature rise in the cable insulation

Solid State Crowbar

ETT based Crowbar

Dimension (WxHxD):
1.1mx0.56mx0.45m

LTT based Crowbar



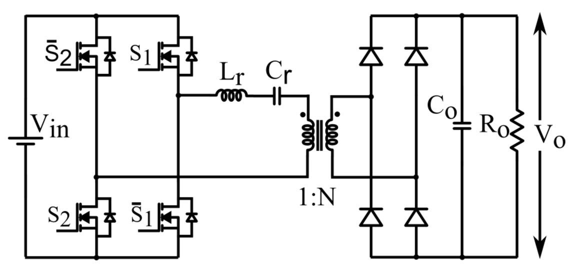
Dimension (WxHxD):
1.0mx0.65mx0.53m

- *This research work led to the first MW power level Solid State Crowbar built in India*
  - Only one manufacturer worldwide for high power SSC (M/s JEMA, Spain)
- Supplied SSC with Light Triggered Thyristor to *Institute for Plasma Research (IPR), Ahmedabad,* where it is currently in operation

Indian patent filed with number "201641009834 dated 21/03/2016" jointly by CDAC & IISc

High Voltage Power Supply (HVPS)

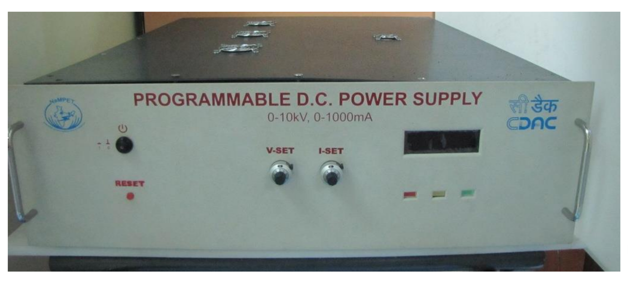
- System performance in the applications where HVPS are used depends on output voltage ripple
  - Image contrast in X-ray and MWT are affected
- Requirement of High Voltage Power Supply
  - V_o=10kV, P_o=10kW, $E_s \leq$ 10J, $\Delta V_o/V_o \leq$ 0.5%



- Storage energy and output ripple are related
  - Switching at high frequency
  - Series Resonant Converter (SRC) used
  - f_s=108kHz , f_r=100kHz, $F=f_s/f_r$, Q=Zc/Ro, $Z_C = \sqrt{L_r/C_r}$

Literature of HVPS

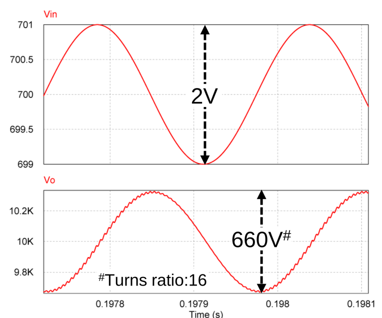
- Output ripple contribution from
  - Switching action
  - Input source ripple
    - Audio Susceptibility (AuS)
- Several modeling methods reported [6]
  - fundamental approximation [7-8]
  - numerically solved
    - hampers the design purpose
- AuS small signal models are not widely studied [9]
  - Available models are numerically solved



Dimension (WxHxD):
0.59mx0.18mx0.65m

1. AuS small signal model

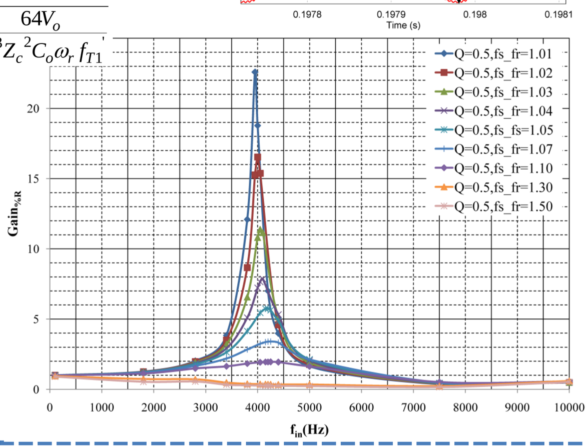
- Modeling involves estimation of:
  - Discrete time state space model using three state variables
  - Cyclic steady state of variables
  - Small signal AuS model and simplification based on practical conditions



$$\frac{v_o(z)}{v_{in}(z)} = \frac{\frac{16}{NZ_C C_o \omega_r}\left\{(z-1) - \frac{4V_o}{NZ_C f_{T1}}\right\}}{(z-1)^3 - \frac{4V_o}{NZ_C f_{T1}}(z-1)^2 + \frac{16}{N^2 Z_C C_o \omega_r}(z-1) - \frac{64V_o}{N^3 Z_C^2 C_o \omega_r f_{T1}}}$$

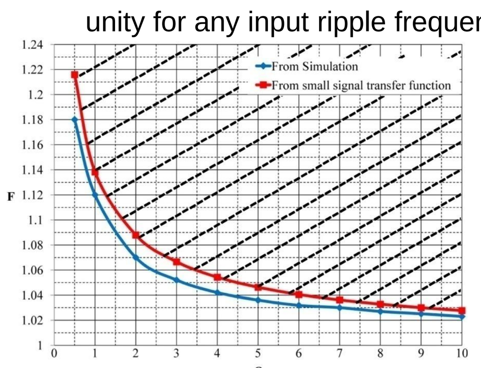
- Analysis shows
  - Resonance for the frequency response, gain as high as 22
  - Frequency where resonance occurs

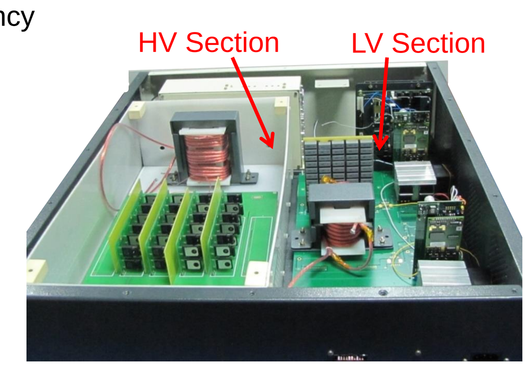
$$\omega_{m,r} = \frac{1}{T_s}\tan^{-1}\sqrt{\frac{16}{N^2 C_o \omega_r Z_c}}$$



2. Design of SRC

- AuS analysis shows
  - there exists a set of values for F and Q where gain is always less than unity for any input ripple frequency





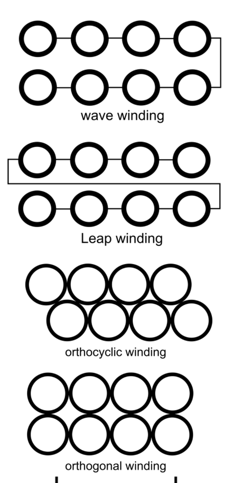
Parameter selection	Conventional method	Proposed method
Q and F	Q=0.65 to 4 F=1.05 to 1.2	Selected based on audio susceptibility gain is less than 1
Turns ratio and tank components	Fundamental approximation	Sampled data modelling

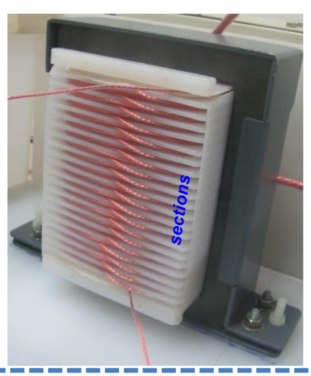
T. G. Subhash Joshi and V. John, "Small Signal Audio Susceptibility Model for Series Resonant Converter," in the Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES), 2016

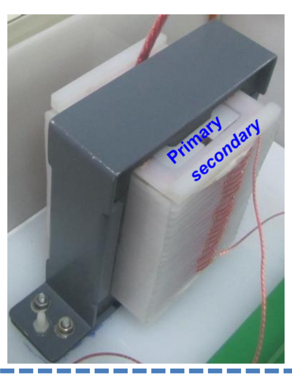
3. HVHF transformer

- Stray capacitance (C_s) is predominant at high frequency
- Experimental iterations

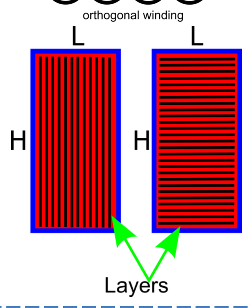
Sl. No.	Winding configuration	C_s	f_r
1	Wave, 0 section, 4layer	63.18pF	76.8kHz
2	Leap, 0 section, 4layer	52.95pF	82.8kHz
3	Leap, 3 section, 4layer	9.60pF	193.5kHz
4	Leap, 7 section, 8layer	8.00pF	216.5kHz
5	Leap, 21 section, 5layer	6.40pF	227.5kHz







Voltage: 700V/10kV
Power: 10kVA
Frequency: 160kHz
WxHxD: 15x12x8cm



Other applications of the research work

- Applications of Solid State Crowbar (SSC)
- **A switch of high peak power**
- ✓ Impulse current waveform generator
  - rise and fall slope of current
- ✓ Electromagnetic launcher
  - strong magnetic field produced by discharging capacitor
- ✓ Partial discharge detection
  - damped AC voltage is produced
- ✓ Rock fragmentation
  - high voltage pulse discharge
- ✓ Electro-magnetic forming
  - produce electromagnetic forces to achieve shaping, joining, cutting
- ✓ ***Protection for MW tube used in plasma generation***

- Applications of High Voltage Power Supply (HVPS)
- **Voltage range in kV dc**
- ✓ Industry
  - Electrostatic precipitator for filtering fine particles
  - Corona generators
  - Dielectric testing
  - Microwave oven
- ✓ Medical
  - ***X-rays***
- ✓ Strategic
  - ***Radar***
  - Particle accelerators
  - Plasma applications

Contributions of the research work

- Crowbar for high power applications
  - Protection device analyzed and verified for energy sensitive load
    1. Modelling of DC fault current and MW tube
    2. Design of di/dt limiting Inductor
    3. Static and dynamic voltage balancing network
    4. Design of mounting clamps for crowbar application
    5. Method for computation of transient thermal impedance for crowbar and method for cable selection
- HVPS for medium power applications
  - Output voltage ripple minimized by proper selection of resonant components without increasing the stored energy
    1. Audio susceptibility small signal model of SRC
    2. Design of SRC
    3. High Voltage High Frequency magnetic design
- All the proposed methods are validated on hardware systems

Patents and publications

1. Indian patent filed with number "201641025723 dated 27/07/2016" jointly by CDAC & IISc
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Funded by:
Ministry of Electronics and Information Technology, Govt. of India
through NaMPET Programme

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Objective of research and applications

Design analysis and experimental validation of

i. Solid State Crowbar (SSC) for the high voltage high power applications

ii. High performance High Voltage Power Supply (HVPS) for medium power applications

- ***Applications of SSC***
  - ✓ Impulse current generator
  - ✓ Electromagnetic launcher
    - ❖ strong magnetic field produced by discharging capacitor
  - ✓ Partial discharge detection
    - ❖ damped AC voltage is produced
  - ✓ Electro-magnetic forming
    - ❖ produce electromagnetic forces to achieve shaping, joining, cutting
  - ✓ ***Protection for Microwave tube (MWT) used in plasma generation***

- ***Applications of HVPS***
  - ✓ Industry
    - ❖ Electrostatic precipitator for filtering fine particles
    - ❖ Corona generators
    - ❖ Dielectric testing
  - ✓ Medical
    - ❖ ***X-rays***
  - ✓ Strategic
    - ❖ ***Radar***
    - ❖ Particle accelerators
    - ❖ Plasma applications

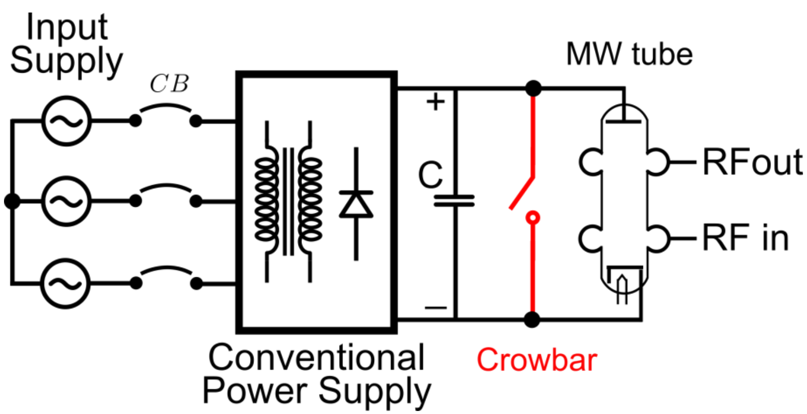
Need for HV pulse power electronics

- System performance in the applications depends on output voltage ripple
  - Image contrast in X-ray and MWT are affected
- Survivability of Microwave Tube (MWT) found in HV applications depends on
  - Stored energy in the HVPS
- HVPS is classified based on the power rating

High power	Topology: *Mains frequency rectifier circuit* ✓ Large output capacitors used to reduce the ripple ✓ Increase the stored energy ✓demands protection mechanism called **Crowbar**
Medium power	Topology: *Switched converters* ✓ Reduce the effect of low frequency input ripple on the output voltage called **Audio susceptibility**
Low power	Topology: *Voltage multiplier circuits*

Solid state crowbar (SSC)

- Requirement of Solid State Crowbar (SSC)
  - Limit the energy in MW tube below 10J



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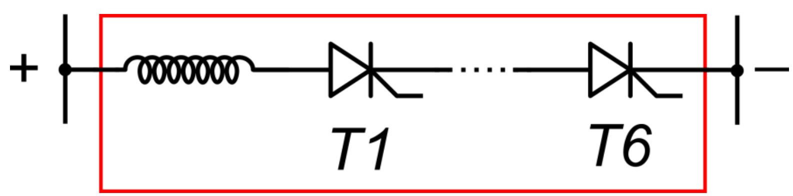

- SSC of 10kV dc, 1kA peak current and 10MW peak power
- Should transfer energy in 10μs

Contributions of the research work on SSC

1. Modelling of
   - ✓ DC fault current in MW tube
   - ✓ Modelling of MW tube
2. Design of di/dt limiting inductor
3. Static and dynamic voltage balancing network
4. Design of mounting clamps for press pack thyristor
5. Other topics
   - ➢ Computation of transient thermal impedance for the thyristor and heatsink combined system
   - ➢ Selection of cable for the pulse power application

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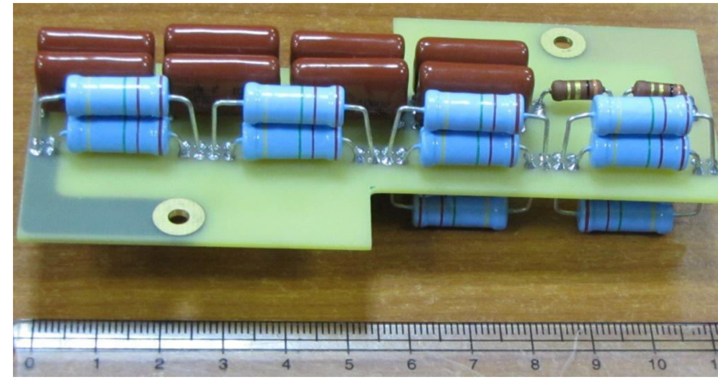

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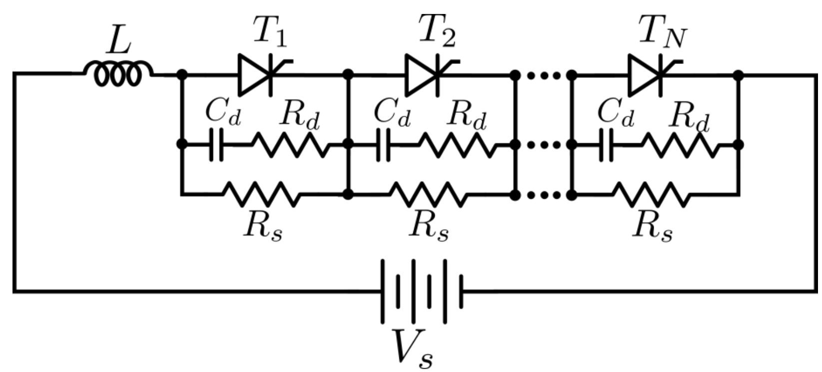

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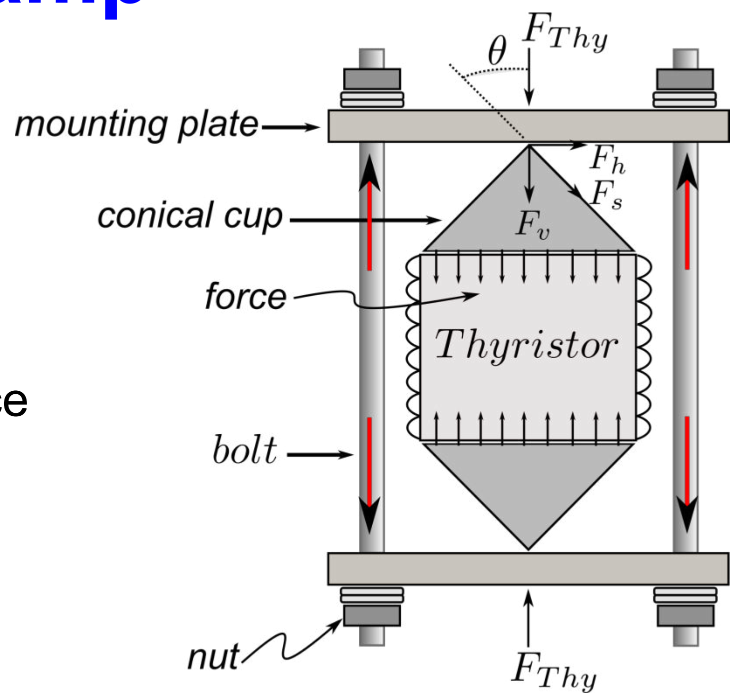

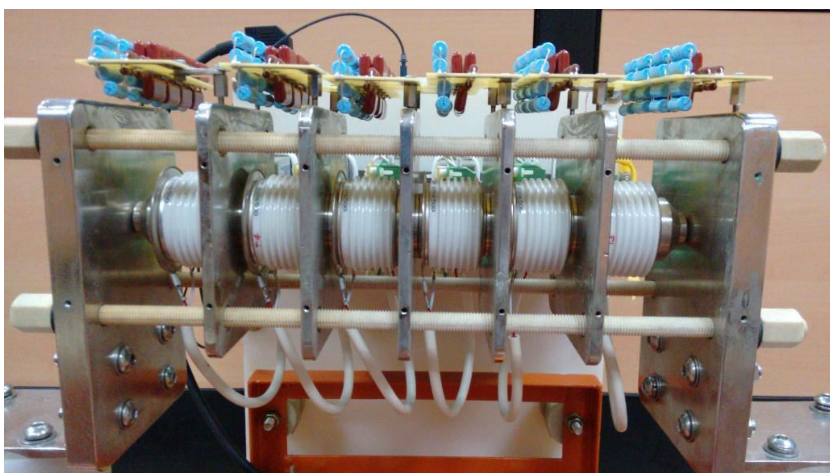

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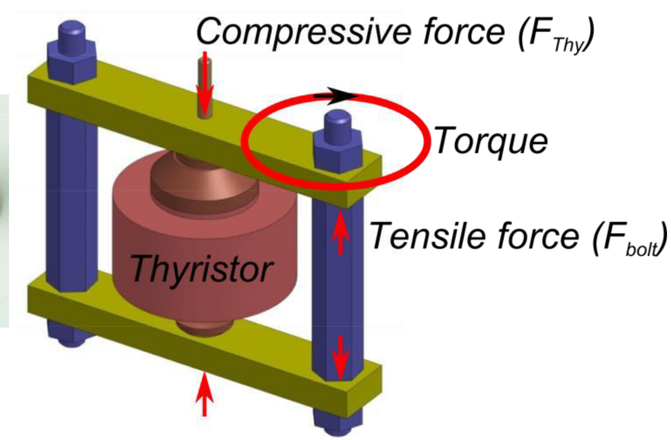

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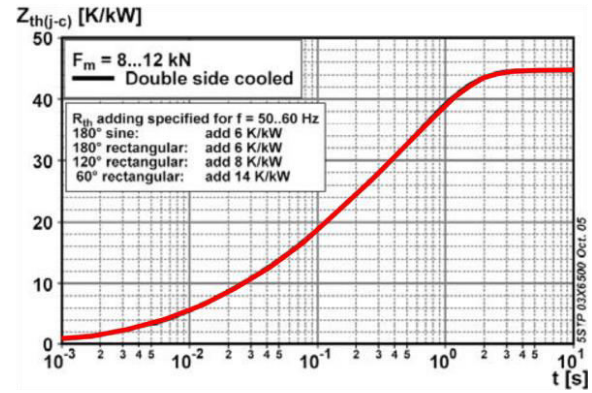

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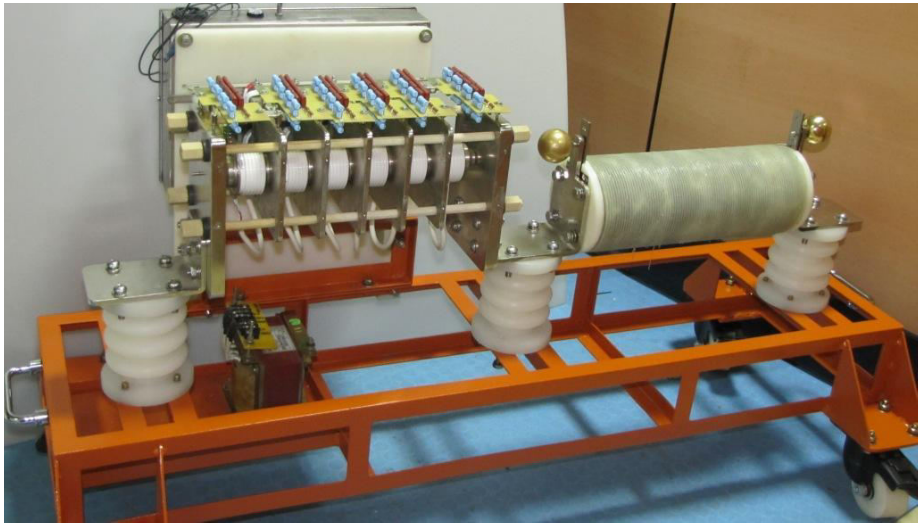
  - High peak current flows for a short duration of time
    - Conventional method of selecting the cable by current density is inappropriate
  - Procedure considers:
    - ambient temperature
    - temperature rise in the cable insulation

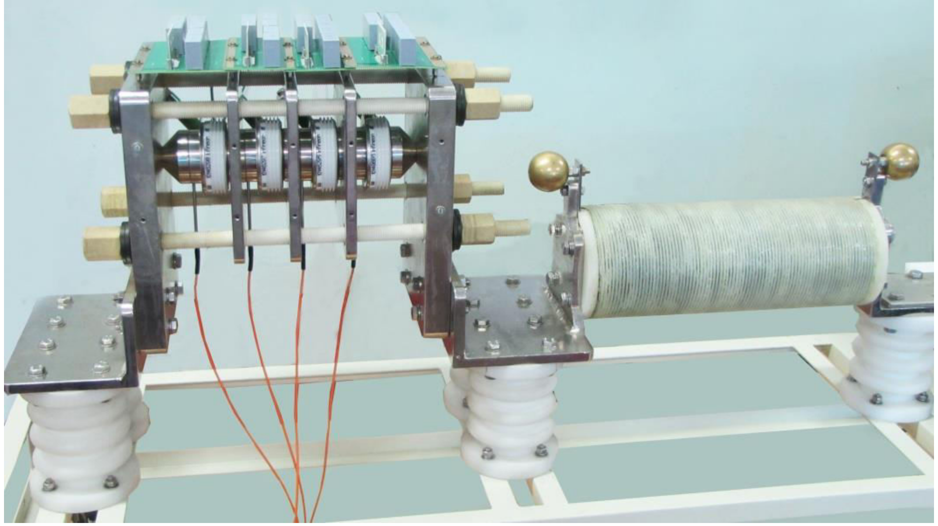
Solid State Crowbar

ETT based Crowbar



Dimension (WxHxD):
1.1mx0.56mx0.45m

LTT based Crowbar



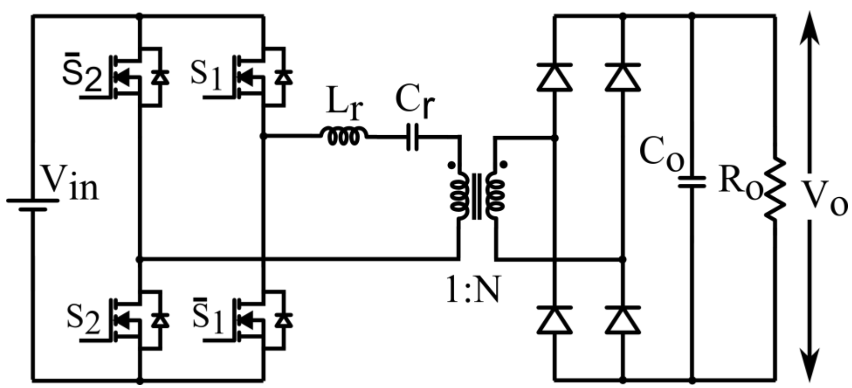
Dimension (WxHxD):
1.0mx0.65mx0.53m

- *This research work led to the first MW power level Solid State Crowbar built in India*
  - Only one manufacturer worldwide for high power SSC (M/s JEMA, Spain)
- Supplied SSC with Light Triggered Thyristor to *Institute for Plasma Research (IPR), Ahmedabad,* where it is currently in operation

Indian patent filed with number "201641009834 dated 21/03/2016" jointly by CDAC & IISc

High Voltage Power Supply (HVPS)

- Requirement of High Voltage Power Supply
  - V_o=10kV, P_o=10kW,
    $E_s \leq$ 10J, $\Delta V_o/V_o \leq$ 0.5%

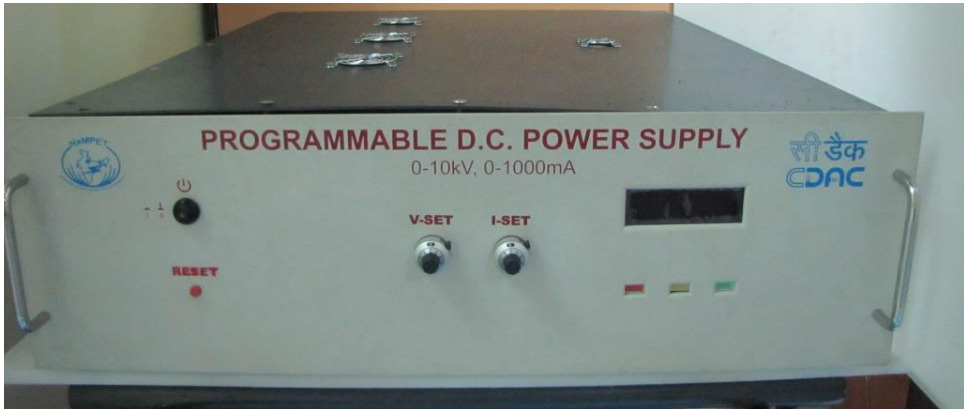


- Storage energy and output ripple are related
  - Switching at high frequency
  - Series Resonant Converter (SRC) used
  - f_s=108kHz , f_r=100kHz, F=f_s / f_r
  - Q=Z_c/R_o, $Z_c = \sqrt{L_r / C_r}$

- Output ripple contribution from
  - Switching action
  - Input source ripple
    - Audio Susceptibility (AuS)
- Several modeling methods reported [6]
  - fundamental approximation [7-8]
  - numerically solved
    - hampers the design purpose
- AuS small signal models are not widely studied [9]
  - Available models are numerically solved

Contributions of the research work on HVPS

1. AuS small signal model of SRC
   - Sampled data modelling method is used [10]
2. Design of SRC
   - minimize the effect of input ripple on output voltage
   - for superior audio susceptibility gain
3. High Voltage High Frequency (HVHF) magnetic design
   - for minimum stray capacitance
   - ensures resonant frequency above switching frequency

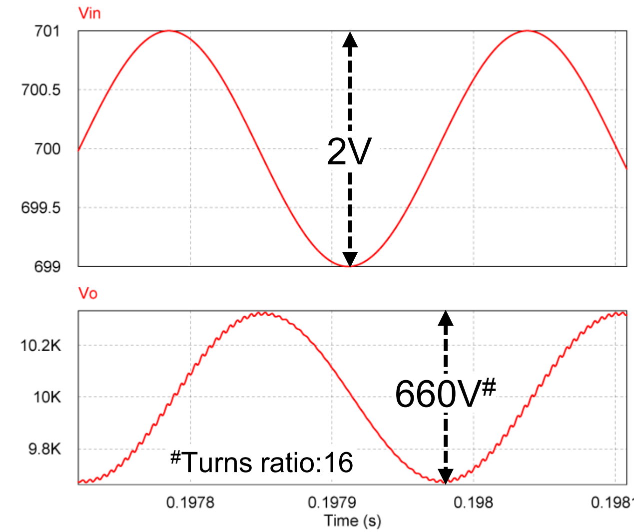


Dimension (WxHxD):
0.59mx0.18mx0.65m

1. AuS small signal model

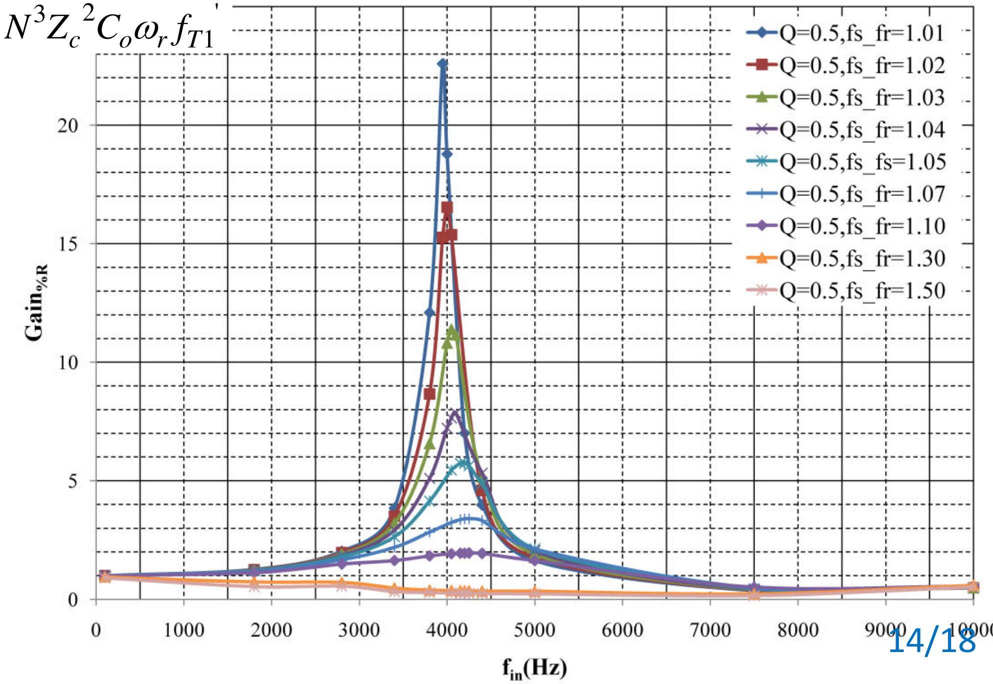
- Modeling involves estimation of:
  - Discrete time state space model using three state variables
  - Cyclic steady state of variables
  - Small signal AuS model and simplification based on practical conditions

$$\frac{v_o(z)}{v_{in}(z)} = \frac{\frac{16}{NZ_cC_o\omega_r}\left\{(z-1)-\frac{4V_o}{NZ_cf_{T1}}\right\}}{(z-1)^3-\frac{4V_o}{NZ_cf_{T1}}(z-1)^2+\frac{16}{N^2Z_cC_o\omega_r}(z-1)-\frac{64V_o}{N^3{Z_c}^2C_o\omega_rf_{T1}}}$$



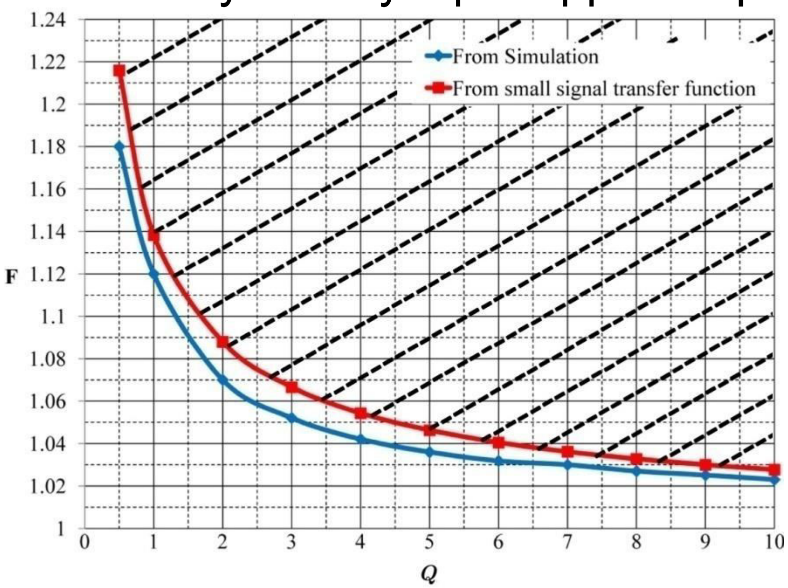
- Analysis shows
  - Resonance for the frequency response, gain as high as 22
  - Frequency where resonance occurs

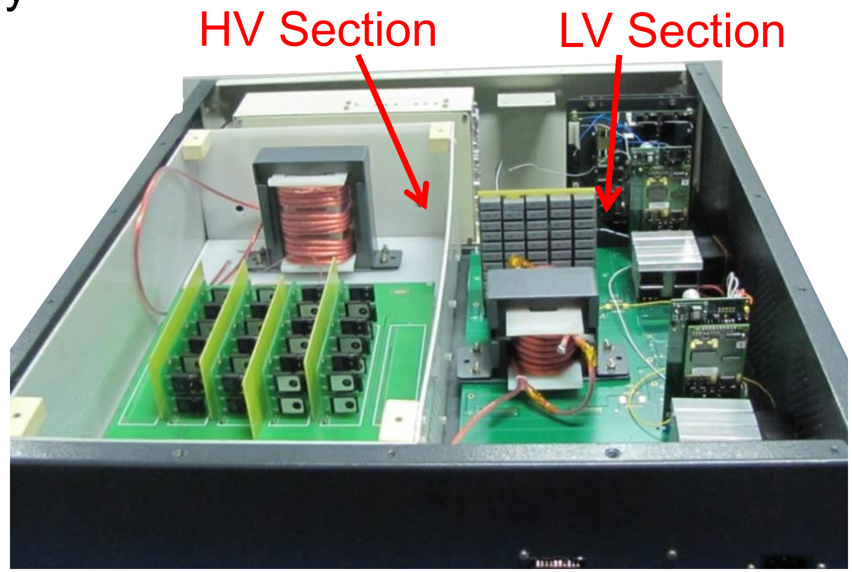
$$\omega_{in,r} = \frac{1}{T_s}\tan^{-1}\left(\sqrt{\frac{16}{N^2C_o\omega_rZ_c}}\right)$$



2. Design of SRC

- AuS analysis shows
  - there exists a set of values for F and Q where gain is always less than unity for any input ripple frequency





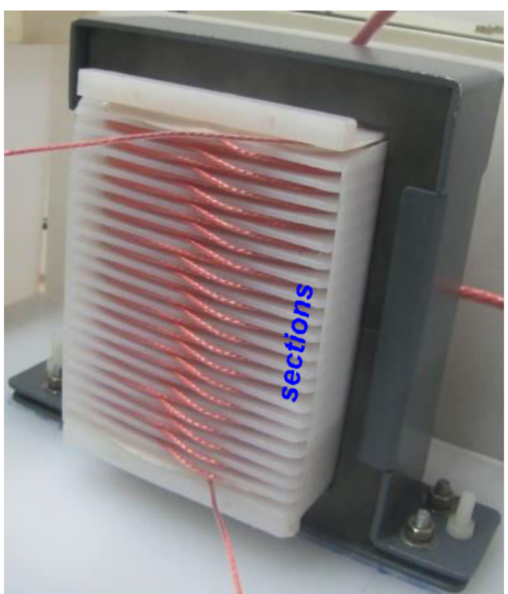
Parameter selection	Conventional method	Proposed method
Q and F	Q=0.65 to 4 F=1.05 to 1.2	Selected based on audio susceptibility gain is less than 1
Turns ratio and tank components	Fundamental approximation	Sampled data modelling

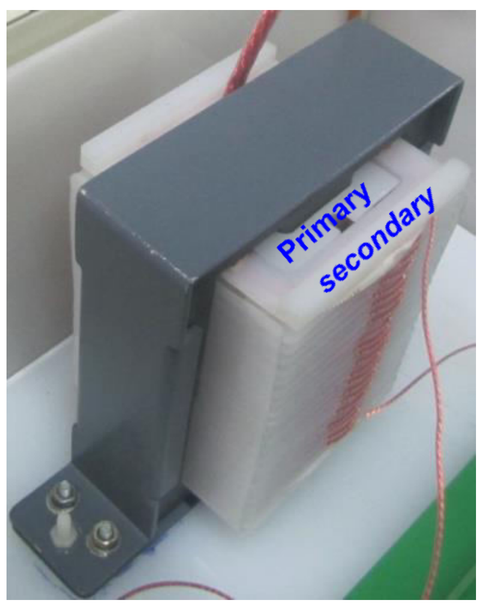
T. G. Subhash Joshi and V. John, "Small Signal Audio Susceptibility Model for Series Resonant Converter," in the Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES), 2016

3. HVHF transformer

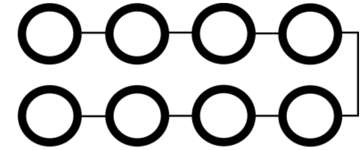
- Stray capacitance (C_s) is predominant at high frequency
- Experimental iterations

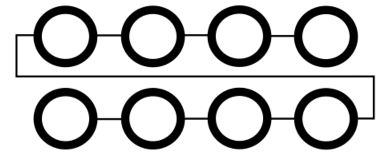
Sl. No.	Winding configuration	C_s	f_r
1	Wave, 0 section, 4layer	63.18pF	76.8kHz
2	Leap, 0 section, 4layer	52.95pF	82.8kHz
3	Leap, 3 section, 4layer	9.60pF	193.5kHz
4	Leap, 7 section, 8layer	8.00pF	216.5kHz
5	Leap, 21 section, 5layer	6.40pF	227.5kHz

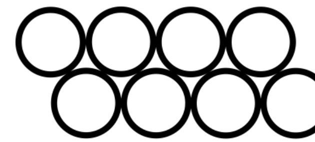


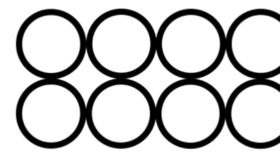


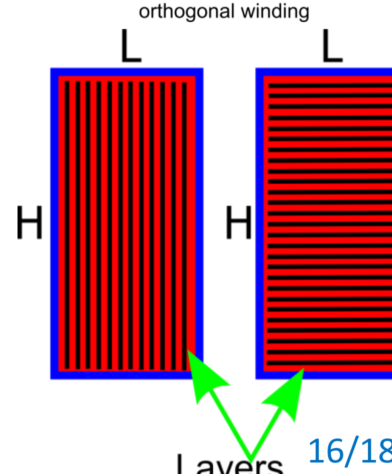
Voltage: 700V/10kV
Power: 10kVA
Frequency: 160kHz
WxHxD: 15x12x8cm


wave winding


Leap winding


orthocyclic winding


orthogonal winding



Conclusions

❖ Crowbar for high power applications

➢ Protection device analyzed and verified for energy sensitive load

1. Modelling of DC fault current and MW tube
2. Design of di/dt limiting Inductor
3. Static and dynamic voltage balancing network
4. Design of mounting clamps for crowbar application
5. Method for computation of transient thermal impedance for crowbar and method for cable selection

❖ HVPS for medium power applications

➢ Output voltage ripple minimized by proper selection of resonant components without increasing the stored energy

1. Audio susceptibility small signal model of SRC
2. Design of SRC
3. High Voltage High Frequency magnetic design

❖ All the proposed methods are validated on hardware systems

THANK YOU

References

1. U.S. patent 2615147, on Electron Tube Protective System, Oct. 21, 1952.
2. Wikipedia, "Thyratron," Available at: http://en.wikipedia.org/wiki/Thyratron, [Accessed: 12th Sept. 2013].
3. R.H. Smith, "The Fault Diverter – A Protective Device for High Powered Electron Tubes", Lawrence Radiation Laboratory Report for U.S. Atomic Energy Commission, August 1957.
4. A. K. Mitra and P. J. Tallerico, "Spark-Gap Crowbar For High-Voltage Power Supply", IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983.
5. J.F. Tooker, P. Huynh, and R.W. Street, "Solid state high-voltage crowbar utilizing series connnected thyristors", Pulsed Power Conference, 2009, Pg. 1439 – 1443.
6. N. Vishwanathan and V. Ramanarayanan, "High voltage dc power supply topology for pulsed load applications with converter switching synchronized to load pulses," in 5th Int. Conf. Power Electronics and Drive Systems (PEDS), Nov. 2003, pp. 618 – 623.
7. V. Vorperian, "High-Q approximation in the small signal analysis of resonant converters," in Proc. IEEE Power Electron. Spec. Conf., June 1985, pp. 707–715.

References

8. R. King and T. Stuart, “Small-signal model of the series resonant converter,” IEEE Trans. Aerosp. Electron. Syst., vol. 21, no. 3, pp. 301– 319, 1985.
9. S. Tian, F. Lee, and Q. Li, “A simplified equivalent circuit model of series resonant converter,” IEEE Trans. Power Electronics, vol. 31, no. 5, pp. 3922–3931, 2016.
10. M. E. Elbuluk, G. C. Verghese, and J. G. Kassakian, “Sampled-data modeling and digital control of resonant converters,” IEEE Trans. Power Electronics, vol. 3, no. 3, pp. 344–354, Jul. 1988.