Efficiency analysis of a capacitor charging power supply for a pulsed klystron-modulator*

J. S. Oh, S. D. Jang, Y. G. Son, M. H. Cho, W. Namkung, PAL/POSTECH, Pohang, Korea

S. C. Ro
Dong-A Hitech Co. Ltd., Busan, Korea

Korean Physical Society
Hanyang University, Korea
October 24 – 26, 2002

* Work supported in part by Pohang Iron and Steel Company (POSCO) and MOST.
Abstract

A current source, inverter power supply is best choice for a capacitor-charging power supply of a pulsed klystron-modulator. Its high frequency technology makes the system size small and the regulation fine. The command-charging feature of the inverter guarantees higher reliability of switching function.

Thermal design is most critical in this power supply so the analysis of the system efficiency is essential. Better efficiency can be obtained through accurate evaluation of power loss distribution.

Design and fabrication detail of an air-cooled 50-kV, 15-kW inverter charging supply are presented. The efficiency and the stability of the power supply are estimated and examined.
Line-type Modulator & Charging Waveform

Voltage Source

Current Source

Voltage $V_{PFN}$

Current $I_{PFN}$

Time

$2V_G$

$2V_G$
Modulator Layout with a Inverter Power Supply

- HV Inverter Power Supply
- ZPFN, N Stage
- Pulse Transformer 1:n
- RINV
- DINV
- Thyratron
- RSNUB
- CSNUB
- RTAIL
- DETAIL
- REOLC
Key Features with a Inverter Power Supply

- High Reliability by Command Charging Function
- Short Circuit Protection
- Small Size by High Frequency Utilization
- Expandability by Parallel Operation
- Easy Maintenance by a Dead Module Replacement
- Flexible Control Interface
- Removal of a Lossy De-Q’ing System
- Removal of a Bulky EOLC Thyrite
Block Diagram of a Inverter Power Supply

INPUT POWER
- EMI Filter
- Rectifier
- PFC
- Inrush Current Limit
- Filter Capacitor

INVERTER
- Resonant Inverter
- H-Bridge & Resonant Components

HIGH VOLTAGE
- High Frequency Transformer
- High Voltage Rectifier

CONTROL
- Gate Drive
- Controls
- V, I Sense
- Temp. Sense
- Remote Control
- Front Panel
- External Interlock

AC Input to HV Output
**Power Supply;**

\[ P_o = \frac{1}{2} V_{DC} I_{AV} = \frac{1}{\pi} \frac{V_{DC}^2}{Z} = f_r E_r \]

\[ I_{AV} = \frac{2}{\pi} I_p, \quad I_p = \frac{V_{DC}}{Z}, \quad E_r = \frac{1}{2} C_r (2V_{DC})^2 \]

**Load;**

\[ P_o = E / T_C = \text{peak power [J/sec]} \]

\[ P_{av} = E / T_P = \text{average power [W]} \]

\[ E = (1/2) C V_{DC}^2, \quad C = \text{load capacitance [F]} \]

\[ T_P = \text{period}, \quad T_C = \text{charging time} \]

\[ T_D = \text{dwell time}, \quad T_I = \text{dead time} \]
Voltage Utilization & Switching Duty

\[ P_{AV} = P_{PEAK} \]
\[ D = \frac{1}{\pi} \frac{V_{DC}^2}{k \_Z} \]

\[ P_{PEAK} = \frac{1}{2} (k \_V_{DC}) I_{AV} = \frac{1}{\pi} \frac{V_{DC}^2}{Z} k \_d \_f \_r \_E \]

\[ I_{AV} = \frac{2}{\pi} I_p \_d \]
\[ I_p = \frac{V_{DC}}{Z}, \quad E_r = \frac{1}{2} C_r (2V_{DC})^2 \]

\[ k \; \text{; Voltage utilization factor} = V_o / V_{DC} \]
\[ d \; \text{; Switching duty} = f_{sw} / f_r \]
\[ D \; \text{; Charging cycle duty} = T_c / T_p \]
Resonant Current & Device Current

\[ I_{AVG} = \frac{2}{\pi} I_p d D, \quad I_{RMS} = \frac{1}{\sqrt{2}} I_p \sqrt{d D} \]

\[ I_{AVG,IGBT} = \frac{1}{2} \left( 2 + k \right) I_{AVG} \]

\[ I_{AVG,FRED} = \frac{1}{2} \left( 2 - k \right) I_{AVG} \]

\[ I_{RMS,IGBT} = \sqrt{1 + k + \frac{k^2}{3}} \sqrt{\frac{1}{2}} I_{RMS} \]

\[ I_{RMS,FRED} = \sqrt{1 - k + \frac{k^2}{3}} \sqrt{\frac{1}{2}} I_{RMS} \]

\[ I_{AVG,TOTAL} = I_{AVG,IGBT} \cdot I_{RMS,TOTAL} = \sqrt{2\left(1 + \frac{k^2}{3}\right)} I_{RMS} \]

\[ P_{IGBT} = 2V_{CE} I_{AVG,IGBT}, \quad P_{FRED} = 2V_f I_{AVG,FRED} \]
Capacitor-Charging Power Supply

**SMART 5015**

- Average Output Power [kW] 15
- Peak Charging Rate [kJ/s] 18
- Maximum Output Voltage [kV] 50
- Average Output Current [A] 0.6
- AC Input Voltage [V\text{RMS}] 480
- Efficiency [%] 94
- Switching Frequency [kHz] 34.5
- Power Factor 0.85
- Air cooling
- 19" rack x 311 mm x 560mm
- 40 kg
Photograph of Inverter Power Supply

- EMI Filter
- Resonant Capacitor
- DC Bank & IGBT Stack
- HV Tank
### Inverter Specifications

**Full Bridge, Series Resonant Converter**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant Frequency</td>
<td>35</td>
<td>[kHz]</td>
</tr>
<tr>
<td>Resonant Impedance</td>
<td>6.5</td>
<td>[Ω]</td>
</tr>
<tr>
<td>Resonant Capacitance</td>
<td>0.7</td>
<td>[μF]</td>
</tr>
<tr>
<td>Resonant Inductance</td>
<td>30</td>
<td>[μH]</td>
</tr>
<tr>
<td>Switch On-Time</td>
<td>14</td>
<td>[μs]</td>
</tr>
<tr>
<td>DC Bank Voltage</td>
<td>650</td>
<td>[V_{DC}]</td>
</tr>
<tr>
<td>Peak Switching Current</td>
<td>200</td>
<td>[A]</td>
</tr>
<tr>
<td>RMS Switching Current</td>
<td>74</td>
<td>[A]</td>
</tr>
<tr>
<td>Average Switching Current</td>
<td>52.5</td>
<td>[A]</td>
</tr>
</tbody>
</table>
Resonant Capacitor CSM 150

Celem Power Capacitor
Conduction Cooled Polypropylene

- Capacitance: 1.2 [µF]
- Maximum Voltage: 500 [Vrms]
- Maximum Current: 300 [Arms]
- Maximum Power: 150 [kVAr]
- Frequency Limit: 700 [kHz]
- Stray Inductance: < 3 [nH]
- Weight: 300 [g]
- Dimension [mm]: 68 x 30 x 30.2
### IGBT Switch

**IGBT IXYS IXDR 30N120 D1**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vces, Collector-Emitter Voltage</td>
<td>1200</td>
<td>[V]</td>
</tr>
<tr>
<td>Ic, Continuous Collector Current @ Tc=90°C</td>
<td>30</td>
<td>[A]</td>
</tr>
<tr>
<td>Vce(ON), Collector-Emitter ON Voltage</td>
<td>2.4</td>
<td>[V]</td>
</tr>
<tr>
<td>Rjc, Junction to Case Thermal Impedance</td>
<td>0.6</td>
<td>[°C/W]</td>
</tr>
<tr>
<td>Tj, Maximum Junction Temperature</td>
<td>150</td>
<td>[°C]</td>
</tr>
<tr>
<td>Td(on), Gate Turn-On Delay</td>
<td>100</td>
<td>[ns]</td>
</tr>
<tr>
<td>Tr, Current Rise Time</td>
<td>70</td>
<td>[ns]</td>
</tr>
<tr>
<td>Td(off), Gate Turn-Off Delay</td>
<td>500</td>
<td>[ns]</td>
</tr>
<tr>
<td>Tf, Current Fall Time</td>
<td>70</td>
<td>[ns]</td>
</tr>
</tbody>
</table>

### Diode

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vf, Maximum Forward Voltage</td>
<td>2.5</td>
<td>[V]</td>
</tr>
<tr>
<td>Qrr, Reverse Recovery Charge</td>
<td>2000</td>
<td>[nC]</td>
</tr>
<tr>
<td>Trr, Reverse Recovery Time</td>
<td>200</td>
<td>[ns]</td>
</tr>
</tbody>
</table>
IGBT Stack Cooling

N; channel number  S; channel space [in.]
D; channel width [in.]  H; channel length [in.]
P; power [W],  Q; air flow rate [CFM]
DTa; air temperature rise [°C]
DPa; pressure drop [in. H2O]
DTs; heat sink temperature rise [°C]

**Forced convection**

\[ Q = 1.74 \frac{P}{D_{Ta}} \]
\[ D_{Pa} = 0.001 \frac{Q^2}{(NSD)^2} \times [1+0.01 \frac{H}{S}] \]
\[ D_{Ts} = 140 \left[ \frac{S}{(N^{0.2} D^{0.2} H)} \right] \times \left( \frac{P}{Q^{0.8}} \right) \]

<table>
<thead>
<tr>
<th>N (channel)</th>
<th>30.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>s (channel thickness)</td>
<td>in</td>
</tr>
<tr>
<td>d (channel width)</td>
<td>in</td>
</tr>
<tr>
<td>h (channel length)</td>
<td>in</td>
</tr>
<tr>
<td>DTa (air temp. diff)</td>
<td>degC</td>
</tr>
<tr>
<td>P (heat)</td>
<td>W</td>
</tr>
<tr>
<td>F (heat removal flow)</td>
<td>CFM</td>
</tr>
<tr>
<td>DP (air press. drop)</td>
<td>in H2O</td>
</tr>
<tr>
<td>DTs (heat sink temp. rise)</td>
<td>degC</td>
</tr>
<tr>
<td>Rth (forced air cooling)</td>
<td>degC/W</td>
</tr>
</tbody>
</table>
Schematic Diagram of High Voltage Section

- High Frequency Transformer
- 7 Sections in Series
- Input from Inverter
- Current Shunt
- Voltage Divider
- RC Snubber
- HV Output
- Voltage Sense
- Current Sense
VMI Z50FG

Vr, Maximum DC Reverse Voltage $5000$ [V]
Io, Average Rectified Current @ $T_L=55$ °C $1.0$ [A]
Ir, Reverse Leakage Current @ $T_L=100$°C $25$ [uA]
Ifsm, 1 Cycle Surge Current @ $T_L=25$ °C, 8.3ms $8$ [A]
Vf, Maximum Forward Voltage $9.0$ [V]
Tj, Maximum Junction Temperature $150$ [°C]
Rjl, Junction to lead Thermal Impedance $6$ [°C/W] @ L = 3mm, $12$ [°C/W] @ L = 6mm
Qrr, Reverse Recovery Charge $100$ [nC]
Trr, Reverse Recovery Time @ $T_c=125$°C $200$ [ns]
Irrm, Reverse Recovery Current $1$ [A]
Cj, Junction Capacitance @ $T_c=25$ °C $16$ [pF]
A. Construction
Core : TDK PE22 UU120x160x21 (2ea)
Primary : 24 turns, Litz wire
Lp = 3.8 [mH], B = 3260 [Gauss]
Secondary : 2100 turns, 7 section
Rectifier : VMI Z50FG

B. Leakage Inductance, $L_l$
$L_l = 4 \pi N_p^2 U_m (\Delta_{gap} + \Sigma \delta_i / 3) / L_m = 21 \mu H$
$N_p = $Primary Turns $= 24$
$U_m = $Mean Circumference of windings $= 20$ cm
$\Delta_{gap} = $Gap Length between Windings $= 1$ cm
$\delta_i = $Thickness of Windings $= 1$ cm
$L_m = $Winding Length $= 9$ cm
HV Tank Cooling

Internal Dimension; 25 x 21 x 21 cm
Internal Volume; 11 l
Circuit Analysis by PSPICE Simulation

\[
\text{ABS}(I(R_{1s})) \quad \text{AVG}(\text{ABS}(I(R_{1s}))) \times \frac{3.14}{2}
\]

\[
V(VOUT) = 480 \times 1.414 \times 3 / 3.14
\]

\[
S(V(VOUT) \times I(C4)) / S(V(FILTER) \times I(L2)) = 0.94
\]

\[
V(VOUT) = 480 \times 1.414 \times 3 / 3.14
\]

\[
0 \quad 10 \quad 20 \quad 30 \quad 40
\]

\[
S(V(VOUT) \times I(C4)) / S(V(FILTER) \times I(L2)) = 0.94
\]

\[
V(VOUT) = 480 \times 1.414 \times 3 / 3.14
\]

\[
0 \quad 10 \quad 20 \quad 30 \quad 40
\]
## Power Loss & Efficiency

**Power Loss**

- IGBT: \(2V_{ce}I_{av} + 2V_fI_f + 0.5Q_{rr}V_{rm}f_{sw}\)
- Snubber: \(0.5C_sV_{dc}^2f_{sw} \times 3\)
- DC Bank: \(2V_fI_{dc} + I_{rms}^2ESR\)
- Resonant Capacitor: \(2\pi f C V_{rms}^2 \tan \delta = I_{rms}^2ESR\)
- Primary Winding: \(R_{dc}F_{ac}I_{rms}^2\)
- Secondary Winding: \(R_{dc}F_{ac}I_{rms}^2\)
- Ferrite Core: \(k f[kHz]^{1.3}B[mT]^{2.5}Volume[m^3]/3.5\)
- Rectifier: \(2V_fI_f + 0.5Q_{rr}V_{rm}f_{sw}\)

### Output Power

- **Power Loss**: 1.2 kW
- **Efficiency**: 92.7%

### Sub Total (Air)

- IGBT: 242 W
- Resonant Capacitor: 44 W
- Snubber: 217 W
- DC Bank: 70 W
- Others: 120 W
- **Sub Total (Air)**: 693 W

### Sub Total (Oil Tank)

- Core: 122 W
- HV Rectifier: 124 W
- Trans. Winding: 247 W
- **Sub Total (Oil Tank)**: 493 W
Measurement Waveform[1]
(Load Capacitance = 216 nF)

Expanded View
Horizontal: 20 μs/div
Vertical: 10 kV/div

Horizontal: 2 ms/div, Vertical: 10 kV/div
Output Current = 0.73 A
Charging Power = 13.2 kJ/sec
Peak Charging Power = 18.2 kJ/sec
Measurement Waveform[2]
(Load Capacitance = 352 nF)

Expanded View
Horizontal : 10 us/div, Vertical : 50 V/div
Resonant Frequency = 35 kHz

Horizontal : 2 ms/div, Vertical : 5 kV/div
Output Current = 0.74 A
Charging Power = 5.7 kJ/sec
Peak Charging Power = 18.6 kJ/sec
Summary

1. **Air cooling for simplicity.**
2. Resonant parameters; \( f_r = 35 \text{ kHz}, \ L_r = 29 \ \mu\text{H}, \ Z_r = 6.5 \ \Omega \). 
3. Peak charging power is 18 kJ/sec with 0.72 A. 
4. Average power is 15 kW with 83% duty factor. 
5. Total power loss is estimated to be 1.2 kW. 
6. System efficiency is about 93%. 
7. Cooling capacity of oil tank is 500 W by forced convection. 
8. **The cooling capability of HV oil tank is limiting factor.**