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

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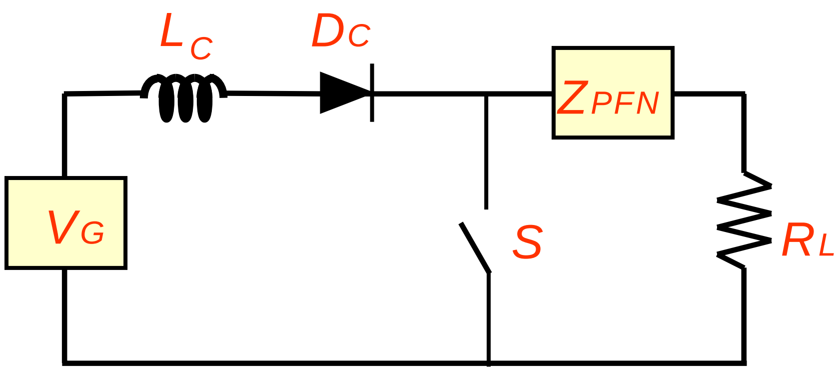
Abstract

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.

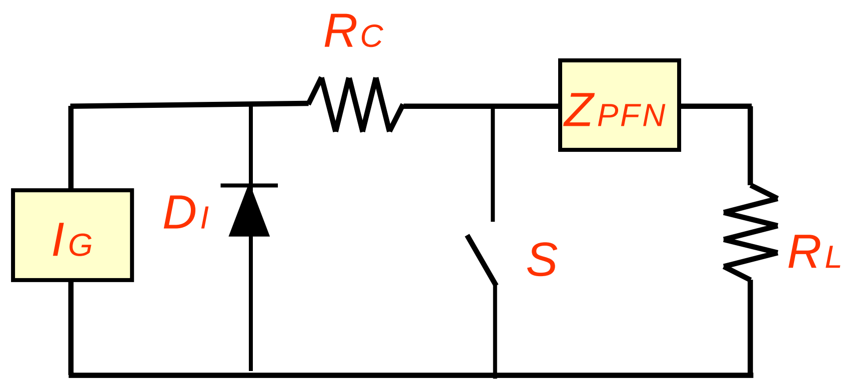
Thermal design is most critical in this power supply so the analysis of the system efficiency is essential. Better efficiency can be obtained through accurate evaluation of power loss distribution.

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.

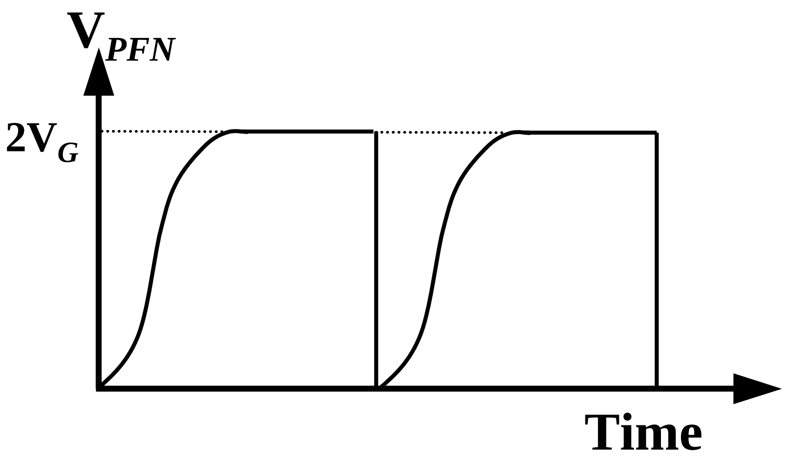
Line-type Modulator & Charging Waveform

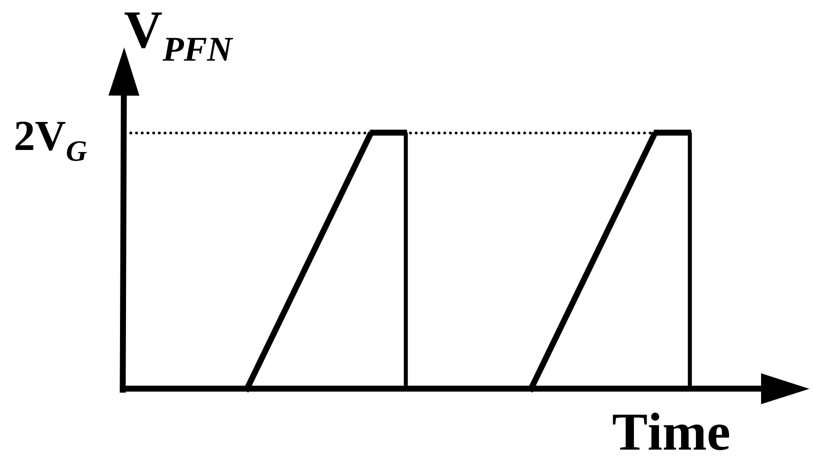


Voltage Source

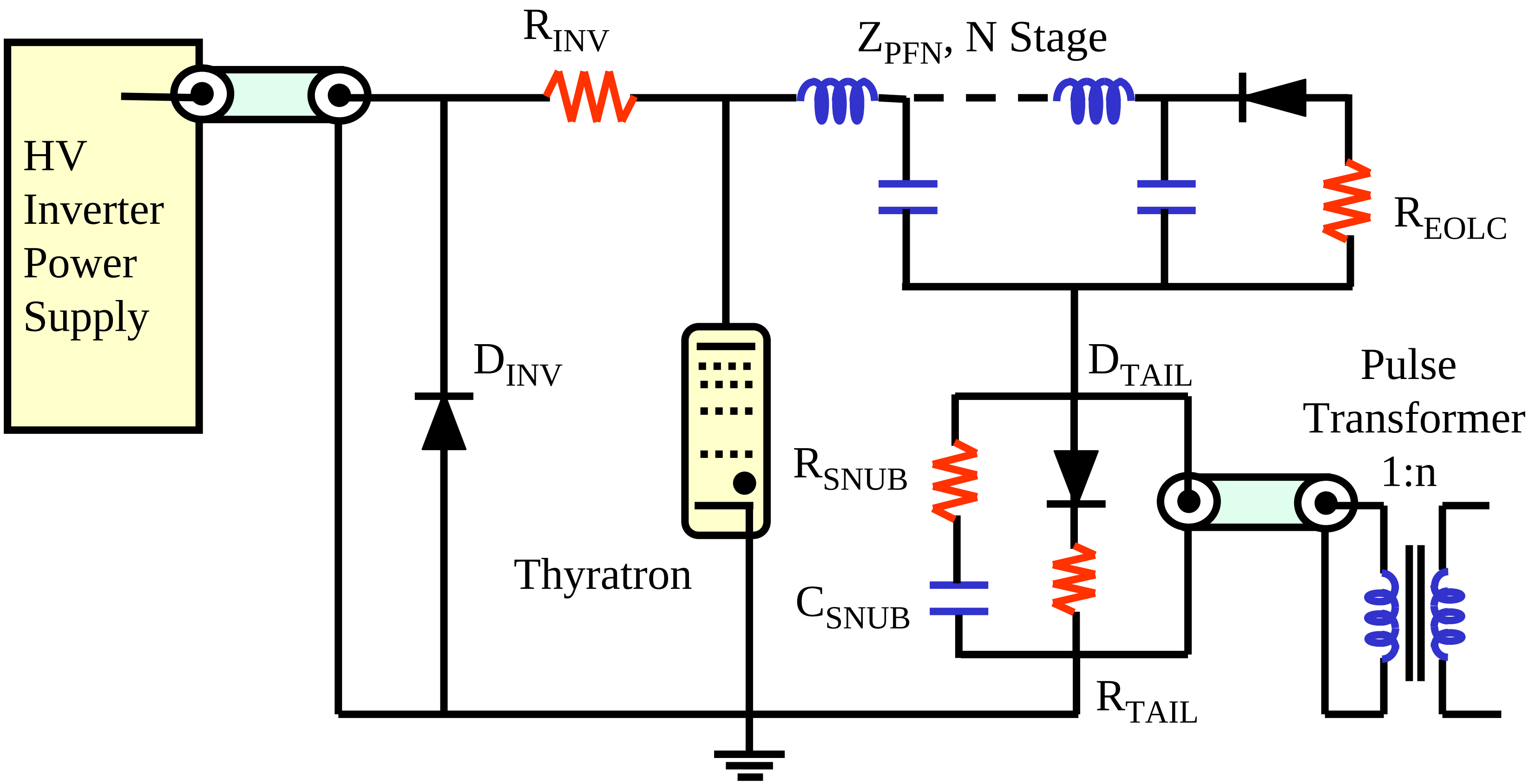


Current Source





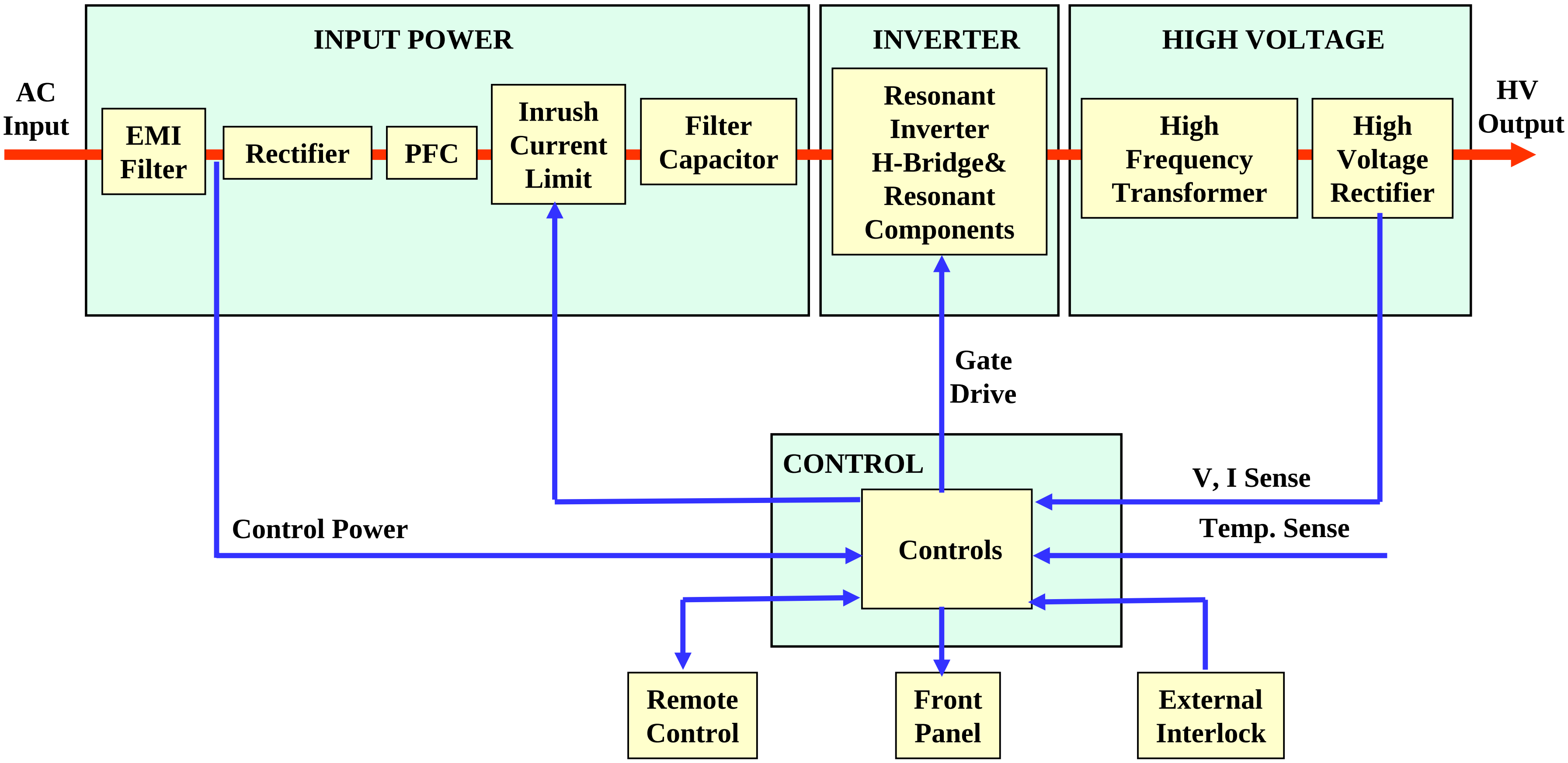
Modulator Layout with a Inverter Power Supply



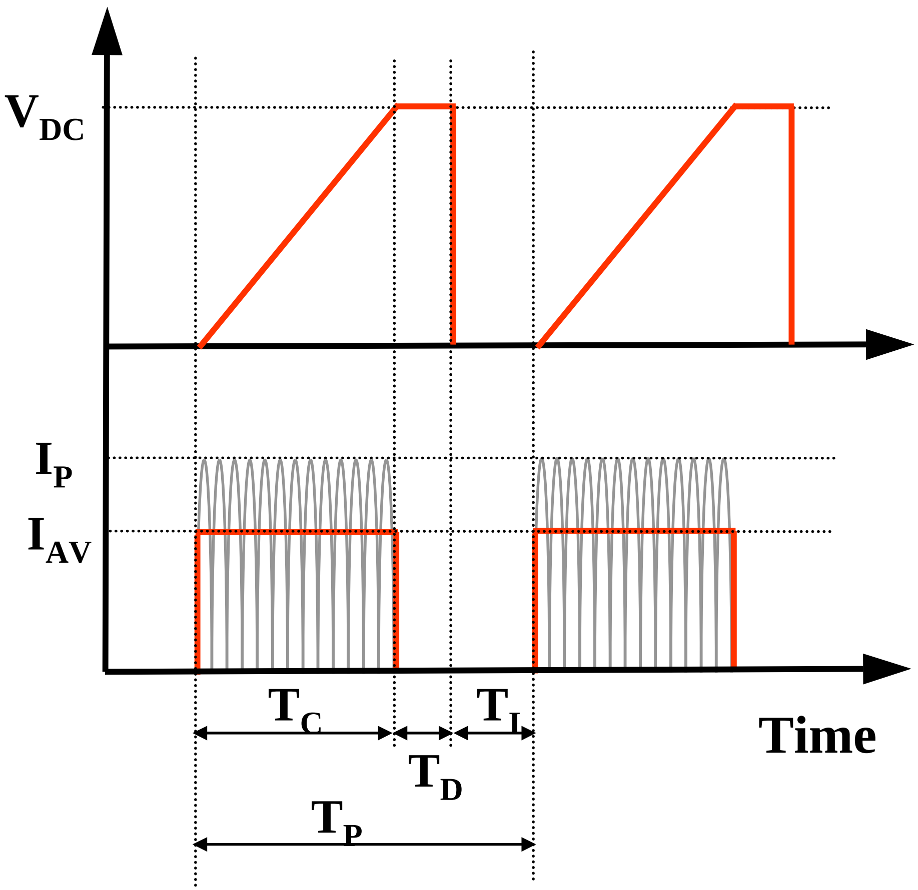
Key Features with a Inverter Power Supply

- 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



Design Basics



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;

$P_o = E / T_C$ = peak power [J/sec]

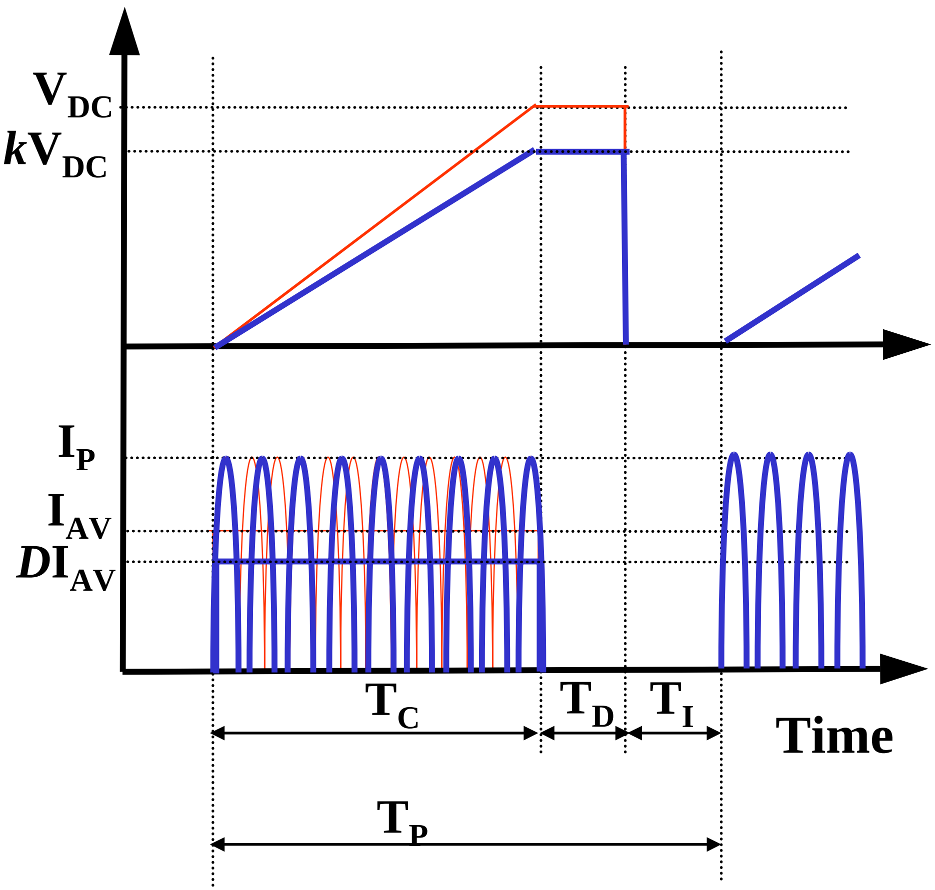
$P_{av} = E / T_P$ = average power [W]

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

T_P = period, T_C = charging time

T_D = dwell time, T_I = dead time

Voltage Utilization & Switching Duty



$$P_{AV} = P_{PEAK}\ D = \frac{1}{\pi}\frac{V_{DC}^{\ 2}}{Z} k\ d\ D$$

$$P_{PEAK} = \frac{1}{2}\left(k\ V_{DC}\right) I_{AV} = \frac{1}{\pi}\frac{V_{DC}^{\ 2}}{Z} k\ d = f_r\ E_r\ k\ d$$

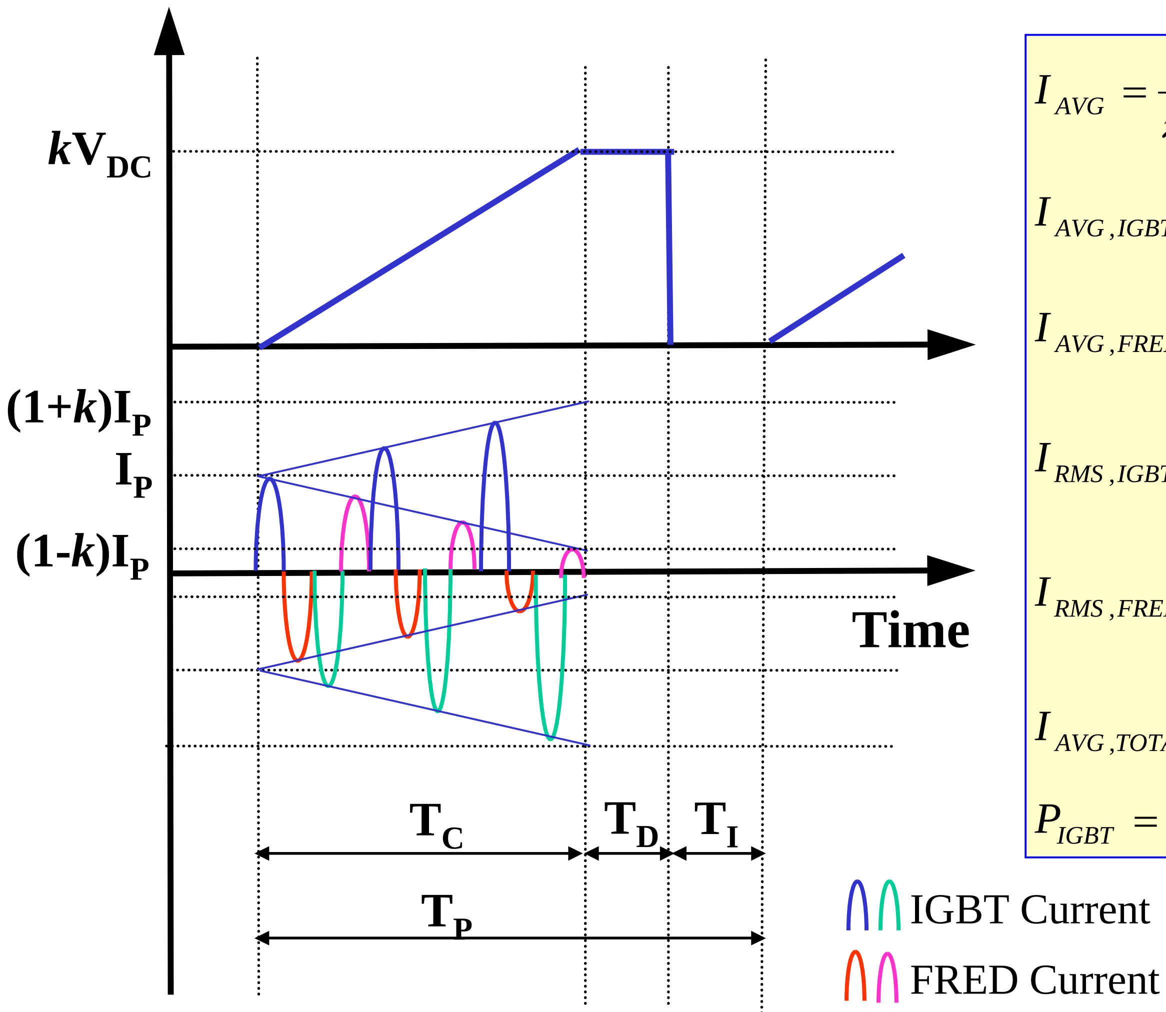
$$I_{AV} = \frac{2}{\pi} I_P\ d, \quad I_P = \frac{V_{DC}}{Z}, \quad E_r = \frac{1}{2} C_r \left(2V_{DC}\right)^2$$

k ; Voltage utilization factor **=** V_O / V_{DC}

d ; Switching duty = ***fsw / fr***

D ; Charging cycle duty = ***Tc / Tp***

Resonant Current & Device Current



$$I_{AVG} = \frac{2}{\pi} I_P d\,D, \quad I_{RMS} = \frac{1}{\sqrt{2}} I_P \sqrt{d\,D}$$

$$I_{AVG,IGBT} = \frac{1}{2}\frac{2+k}{2} I_{AVG}$$

$$I_{AVG,FRED} = \frac{1}{2}\frac{2-k}{2} I_{AVG}$$

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

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

$$I_{AVG,TOTAL} = I_{AVG}, \; I_{RMS,TOTAL} = \sqrt{2(1+\frac{k^2}{3})}\; I_{RMS}$$

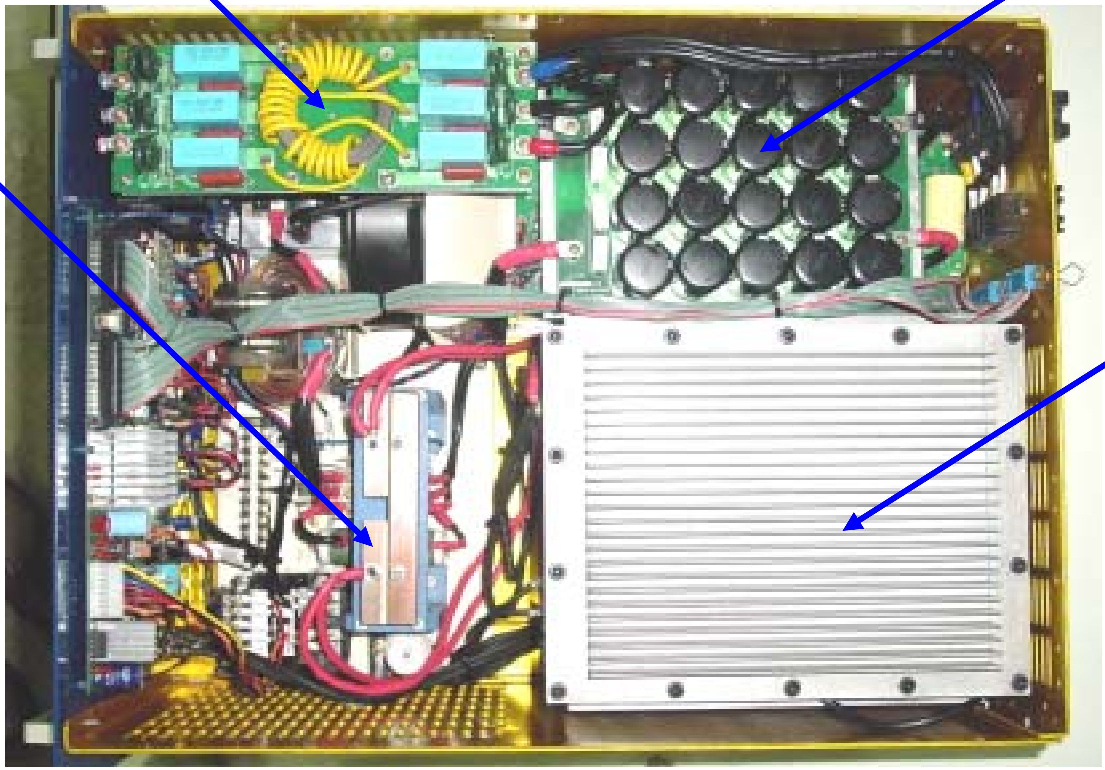
$$P_{IGBT} = 2V_{CE} I_{AVG,IGBT}, \; P_{FRED} = 2V_f I_{AVG,FRED}$$

Capacitor-Charging Power Supply

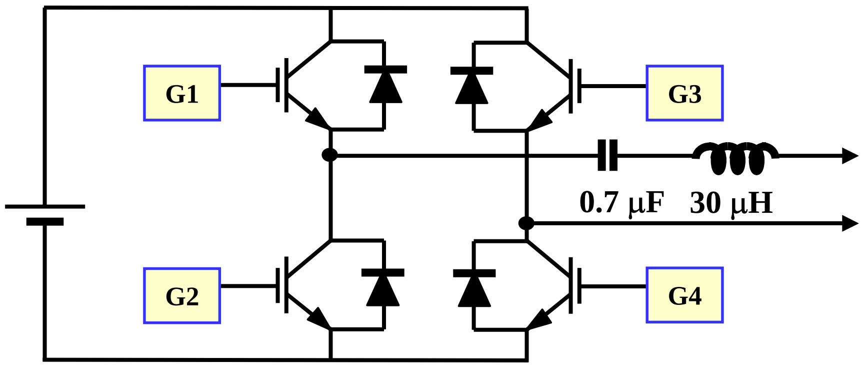
SMART 5015

• 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_{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



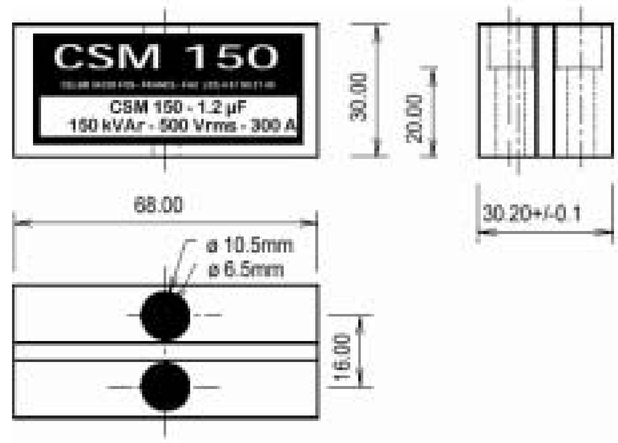
Inverter Specifications



Full Bridge,
Series Resonant Converter

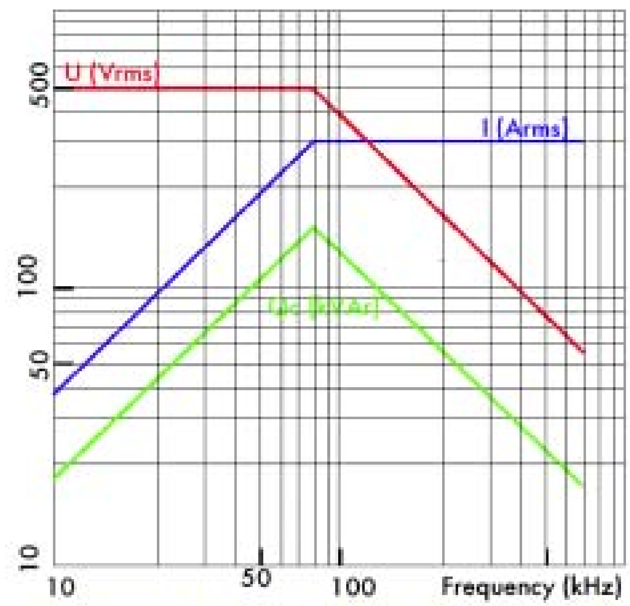
Resonant Frequency	**35**	**[kHz]**
Resonant Impedance	**6.5**	**[Ω]**
Resonant Capacitance	**0.7**	**[μF]**
Resonant Inductance	**30**	**[μH]**
Switch On-Time	**14**	**[μs]**
DC Bank Voltage	**650**	**[V_{DC}]**
Peak Switching Current	**200**	**[A]**
RMS Switching Current	**74**	**[A]**
Average Switching Current	**52.5**	**[A]**

Resonant Capacitor CSM 150



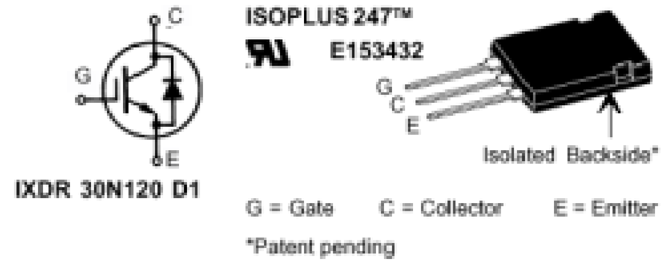
Celem Power Capacitor
Conduction Cooled Polypropylene

- **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**



CSM/CSP 150 1.2 µF - 500 Vrms - 300 Arms - 150 kVAr

IGBT Switch



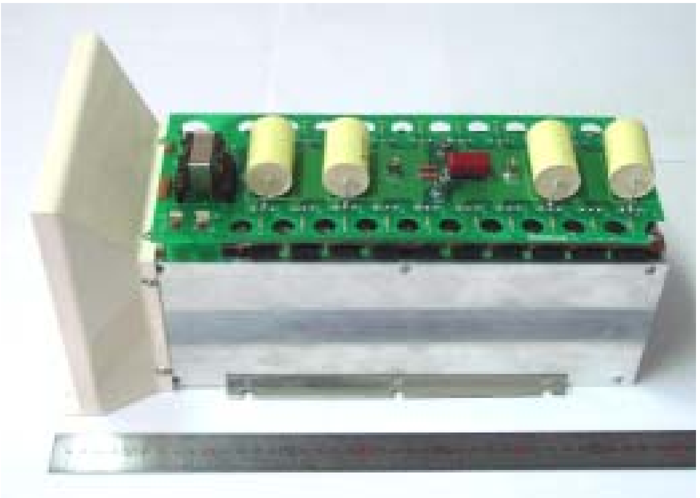
IGBT IXYS IXDR 30N120 D1

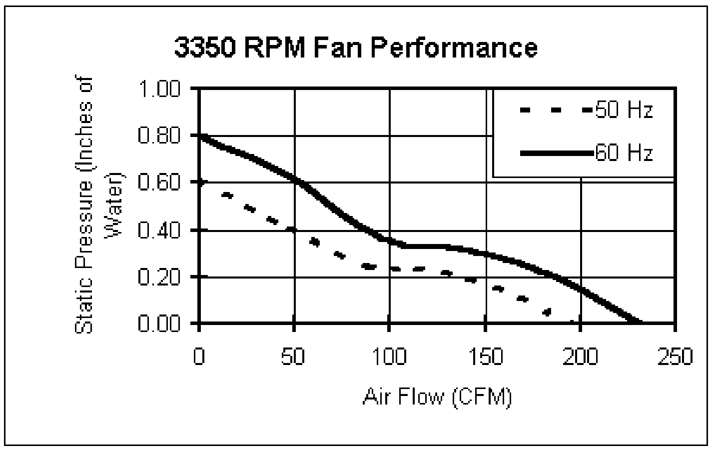
Vces, Collector-Emitter Voltage	**1200**	**[V]**
Ic, Continuous Collector Current @ Tc=90°C	**30**	**[A]**
Vce(ON), Collector-Emitter ON Voltage	**2.4**	**[V]**
Rjc, Junction to Case Thermal Impedance	**0.6**	**[°C/W]**
Tj, Maximum Junction Temperature	**150**	**[°C]**
Td(on), Gate Turn-On Delay	**100**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

Diode

Vf, Maximum Forward Voltage	**2.5**	**[V]**
Qrr, Reverse Recovery Charge	**2000**	**[nC]**
Trr, Reverse Recovery Time	**200**	**[ns]**

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 [^{o}C]
DPa; pressure drop [in. H_2O]
DTs; heat sink temperature rise [^{o}C]

Forced convection

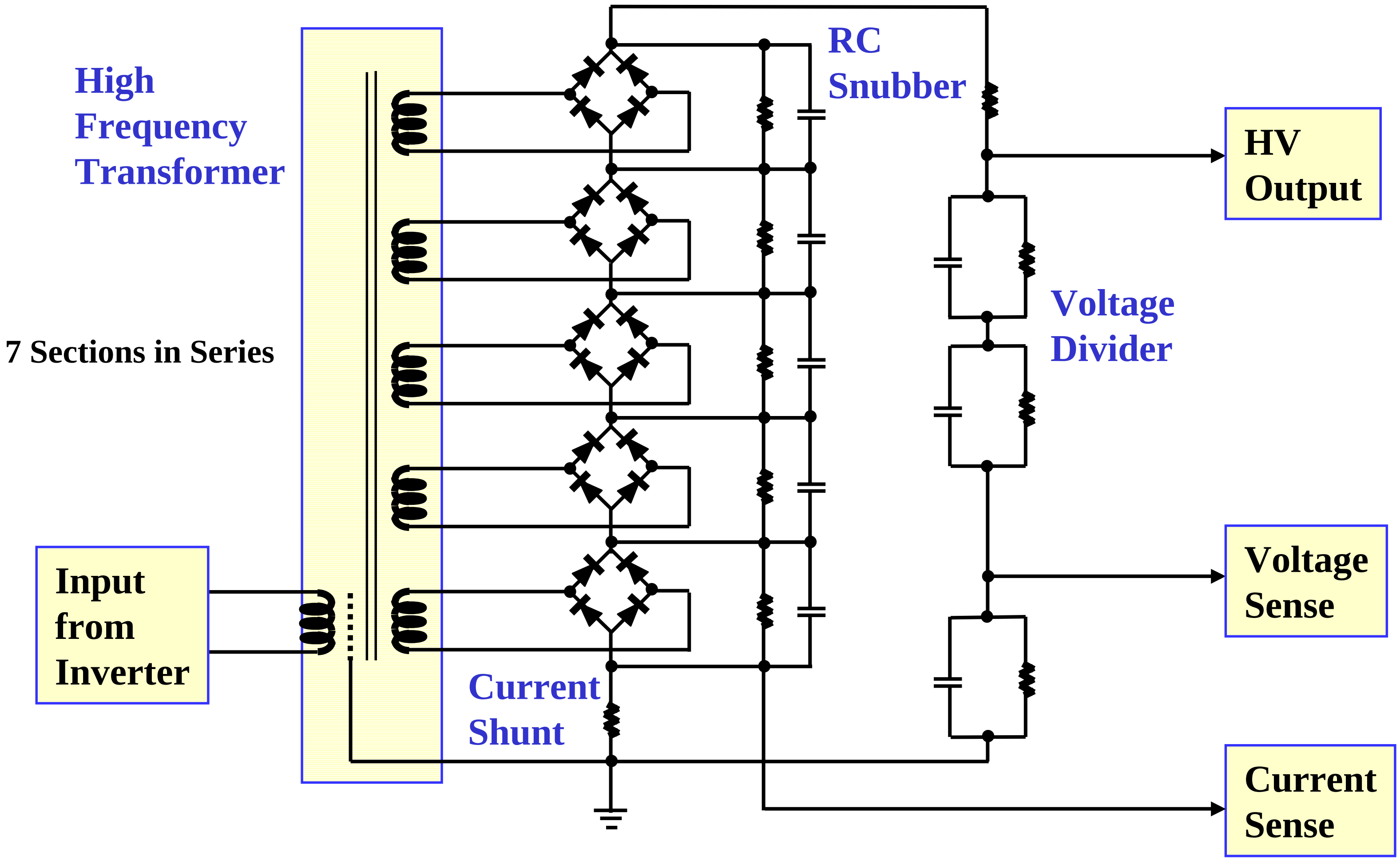
$Q = 1.74\ P / DTa$

$DPa = 0.001\ Q^2 / (NSD)^2 \times [1+0.01\ (H/S)]$

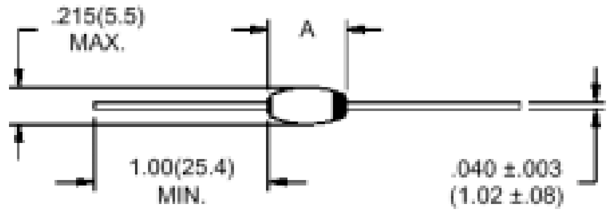
$DTs = 140\ [\ S / (N^{0.2}\ D^{0.2}\ H)\ ] \times (\ P / Q^{0.8}\ )$

N (channel)		30.00
s (channel thickness)	in	0.16
d (channel width)	in	4.57
h (channel length)	in	11.81
DTa (air temp. diff)	degC	4.00
P (heat)	W	350.00
F (heat removal flow)	CFM	152.25
DP (air press. drop)	in H2O	0.09
DTs (heat sink temp. rise)	degC	4.38
Rth (forced air cooling)	degC/W	0.01

Schematic Diagram of High Voltage Section



HV Rectifier Diode

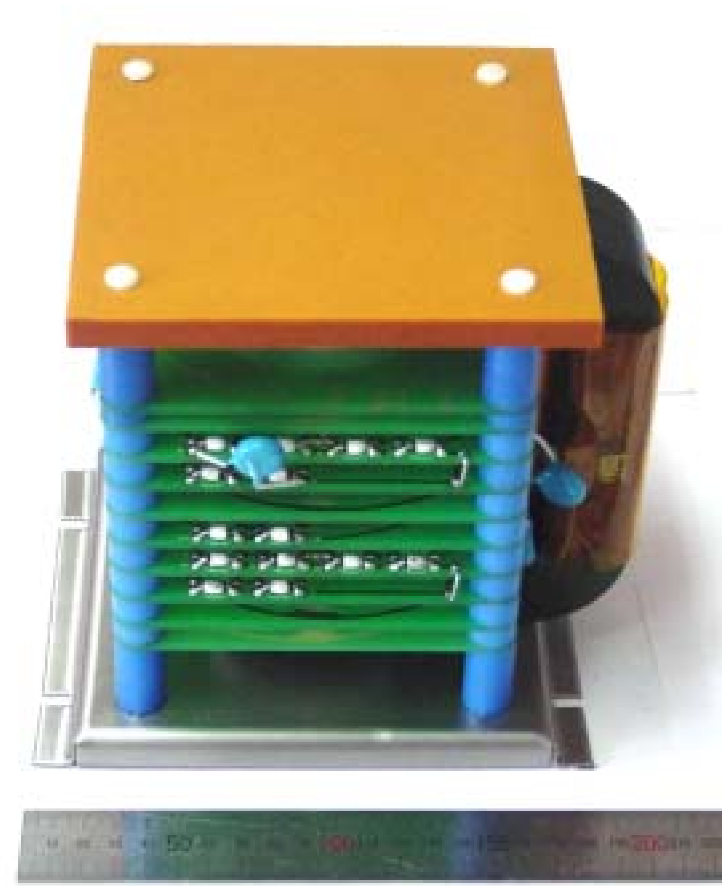


Part	A
Z25FG Z50FG	.350(8.89) MAX.
Z100FG	.400(10.16) MAX.

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 @ Tc=125°C	**200**	**[ns]**
Irrm, Reverse Recovery Current	**1**	**[A]**
Cj, Junction Capacitance @ Tc=25 °C	**16**	**[pF]**

High Voltage Transformer & Rectifier



A. Construction

Core : TDK PE22 UU120x160x21 (2ea)

Primary : 24 turns, Litz wire

L_p = 3.8 [mH], B = 3260 [Gauss]

Secondary : 2100 turns, 7 section

Rectifier : VMI Z50FG

B. Leakage Inductance, L_l

$L_l = 4 \pi N_p^2 U_m (\Delta_{gap} + \Sigma\delta_i /3) / L_m = 21\ \mu H$

Np = Primary Turns = 24

Um = Mean Circumference of windings =20 cm

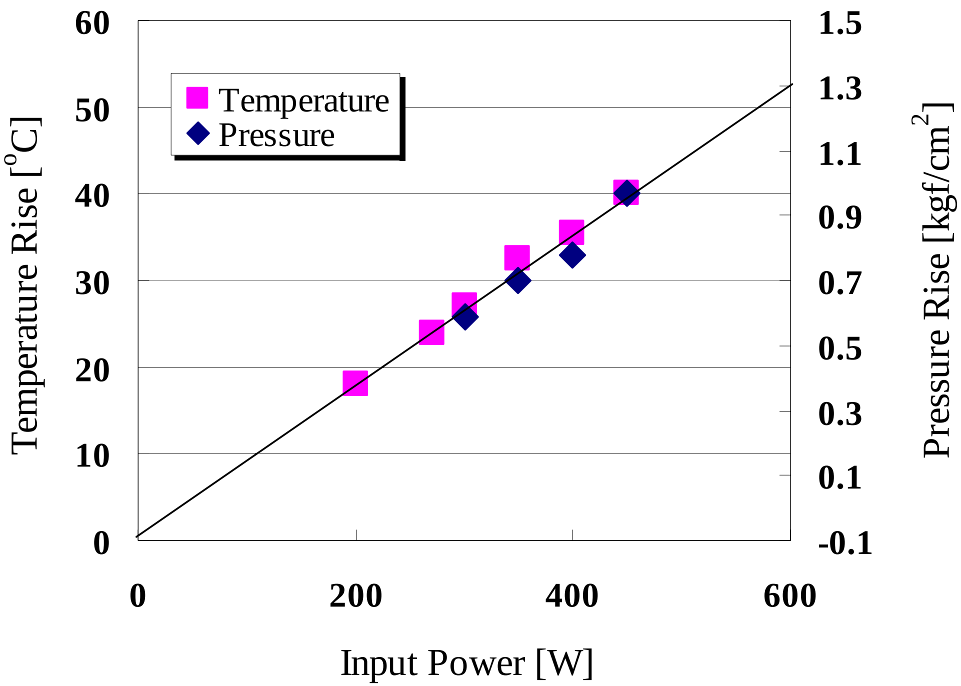
Δ_{gap} = Gap Length between Windings = 1 cm

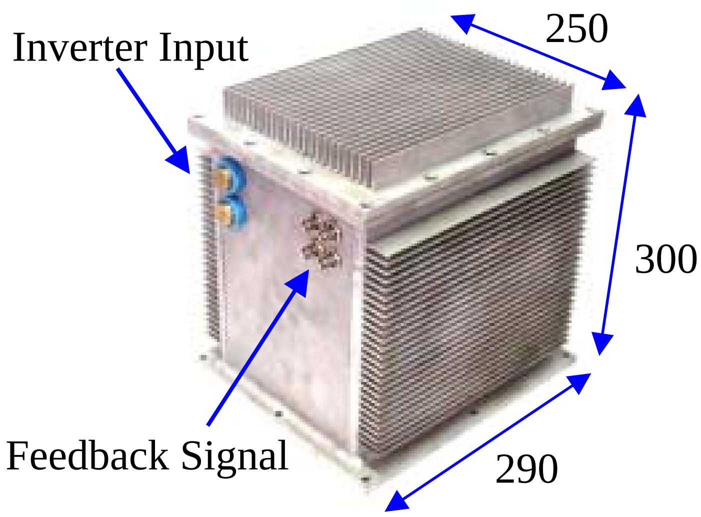
δ_i = Thickness of Windings = 1 cm

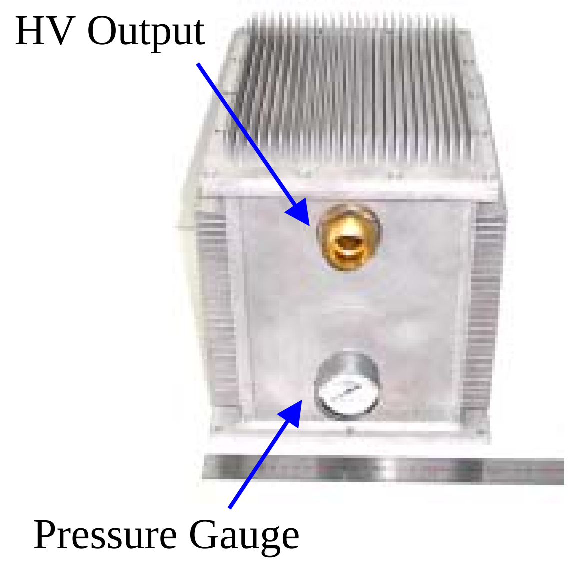
Lm = Winding Length = 9 cm

HV Tank Cooling

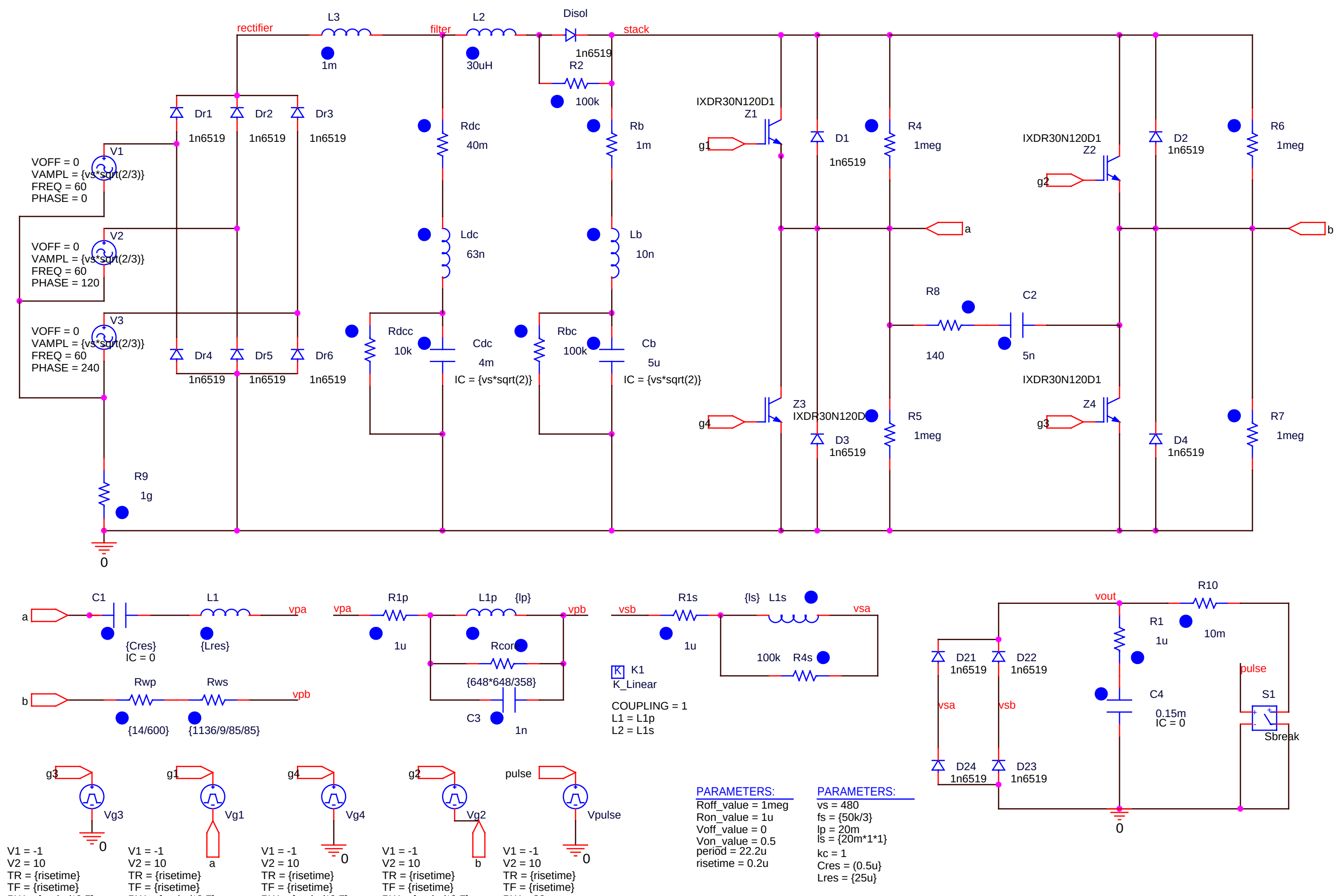
Internal Dimension; 25 x 21 x 21 cm
Internal Volume; 11 *l*





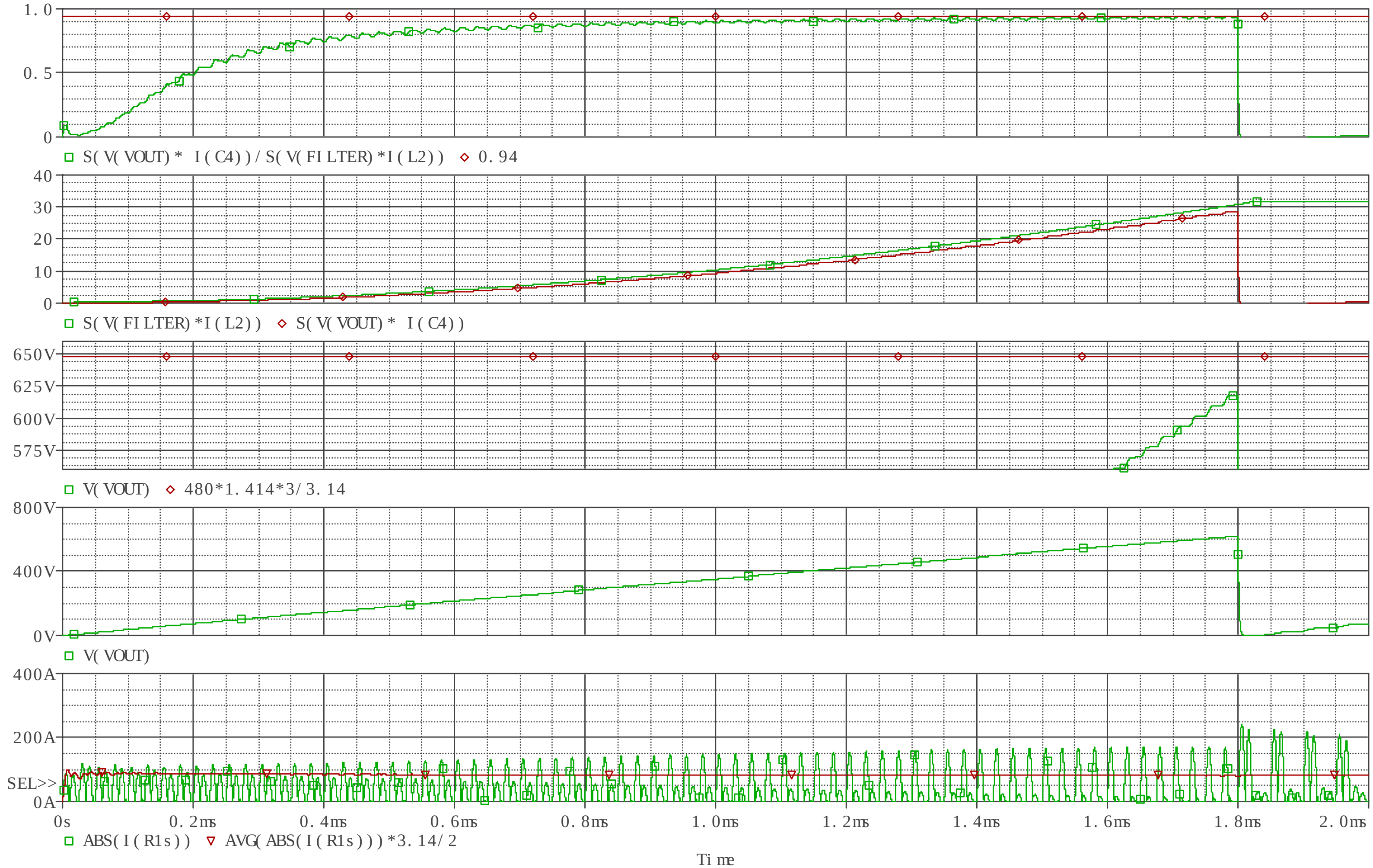


Circuit Diagram of PSPICE Simulation



Vo = 648 V, To = 22.2 usec, Co = 0.5 uF
Lo = 25 uH, Zo = 7.1 Ohm, Ip = 51 A
n = 85, Is = 0.6 A, Vs = 55 kV

Circuit Analysis by PSPICE Simulation



Power Loss & Efficiency

Power Loss

IGBT; 2Vce Iav + 2Vf If + 0.5 Qrr Vrm fsw

Snubber; 0.5 Cs Vdc^2 fsw x 3

DC Bank; 2Vf Idc + $Irms^2$ ESR

Resonant Capacitor; 2 π f C $Vrms^2$ tan δ = $Irms^2$ ESR

Primary Winding; Rdc Fac $Irms^2$

Secondary Winding; Rdc Fac $Irms^2$

Ferrite Core; k $f[kHz]^{1.3}$ $B[mT]^{2.5}$ Volume[m^3] / 3.5

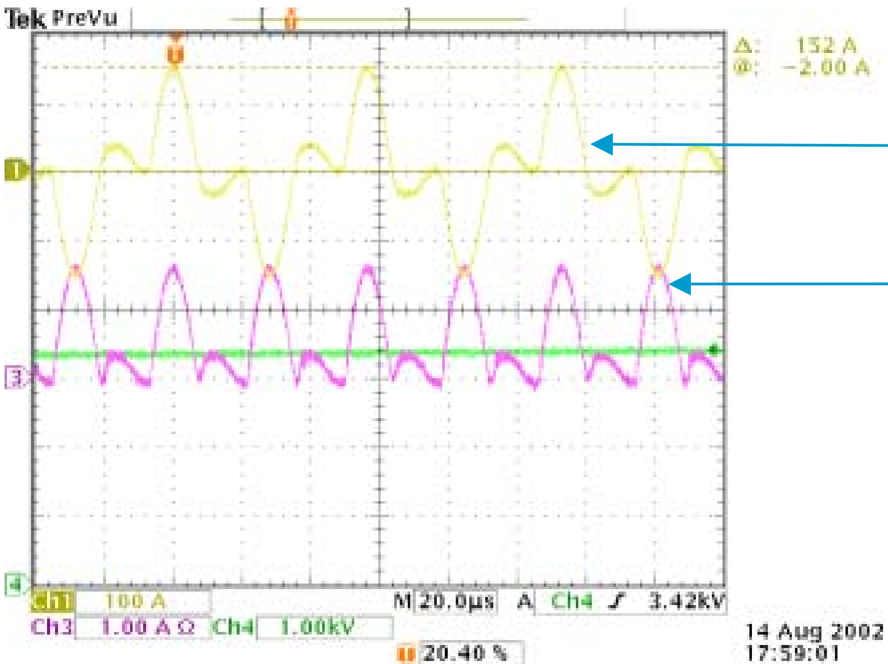
Rectifier; 2Vf If + 0.5 Qrr Vrm fsw

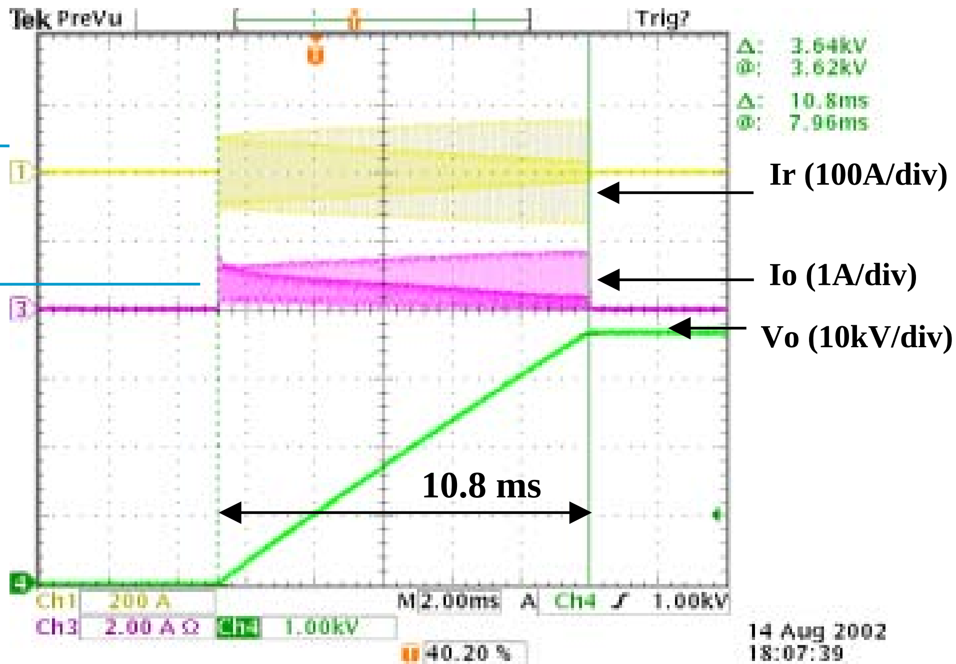
Output Power 15 kW
Power Loss 1.2 kW
Efficiency 92.7 %

IGBT	242 W
Resonant Capacitor	44 W
Snubber	217 W
DC Bank	70 W
Others	120 W
Sub Total (Air)	693 W
Core	122 W
HV Rectifier	124 W
Trans. Winding	247 W
Sub Total (Oil Tank)	493 W

Measurement Waveform[1]

(Load Capacitance = 216 nF)



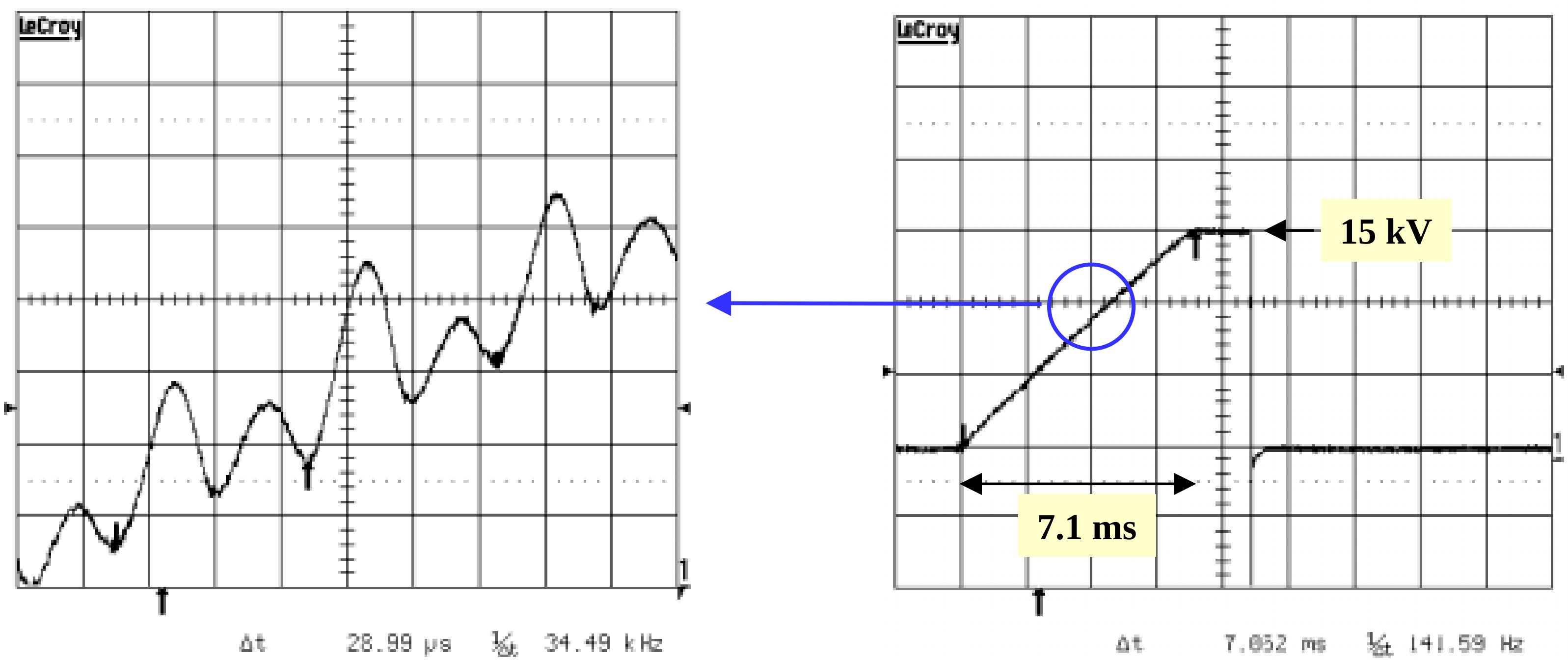


Expanded View
Horizontal : 20 us/div
Vertical : 10 kV/div

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; fr = 35 kHz, Lr = 29 μH, Zr = 6.5 Ω.
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.***