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Design of Planar Transformer and Inductor for 7 kilo-Watt Application

Standard Questions for any Application

1. Power Topology
2. Frequency
3. Input Voltage Range – minimum to maximum
4. Output Voltage
5. Output Power
6. Dielectric and Creepage requirements and Standards.
7. Mechanical Constraints – e.g. usually low-profile height for planar

Power Topologies [Circuits]

1. Forward – 2 types --Active Clamp Forward [ACF] or Diagonal Bridge [2-transistor]
2. Flyback – [3] modes – Continuous [CCM], Discontinuous [DCM], Borderline [BCM]
3. Push-Pull
4. Phase Shifted Full Bridge – Center Tap or Current Doubler
5. Dual Active Bridge [DAB] – popular use in bi-directional converters for EV charging.
6. LLC [CLLC, etc]

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Standard Questions for any Application

1. Power Topology: Full Bridge to Current Doubler
2. Frequency: 75-200 KHz
3. Input Voltage Range [minimum to maximum]: 165-320
4. Output Voltage: 28
5. Output Power: 7KW
6. Mechanical Constraints – Low Profile Planar. Thermal conduction

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The customer had a TI Reference Design in mind: TIDA-020031
Automotive 400-V battery to 12-V, 3.6-kW DC/DC converter reference design

Source: https://www.ti.com/tool/TIDA-020031

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$V_{in} := 165$ $V_{inmax} := 320$ $V_{out} := 28$

$N_p := 5$ $N_s := 2$ $freq := 75 \cdot 10^3$ $freq = 75\,KHz$

$Reg := 1.03$ $A_c := 5.66$ $l_m := 9.3$

$Vol := l_m \cdot A_c$ $Vol = 52.638$

$$D_{max} := \frac{V_{out}}{V_{in}} \cdot \frac{N_p}{N_s} \cdot 1 \cdot Reg$$ $D_{max} = 0.437$ $D_{max} \cdot 2 = 87.394\,\%$

$$Tp := \frac{1}{freq}$$ $Tp = 13.333\,uSec$

$t_{on} := D_{max} \cdot Tp$ $t_{on} = 5.826\,uSec$

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$$B_{pkpk} := \frac{V_{in} \cdot t_{on} \cdot 10^8}{N_p \cdot A_c} \qquad B_{pkpk} = 3.397 \times 10^3$$

$$B_{rms} := \sqrt{\frac{2}{Tp} \cdot \int_0^{t_{on}} \left(\frac{V_{in} \cdot t_{on} \cdot 10^8}{2 \cdot N_p \cdot A_c} \right)^2 dTp} \qquad B_{rms} = 1.588 \times 10^3$$

$B := B_{rms} \cdot 10^{-4}$ $\quad B = 0.159$ $\quad$ RMS Flux in Tesla

$Temp := 65$ $\quad C_m := 5.12$ $\quad x := 1.34$ $\quad y := 2.66$

$C_{t2} := 5.48 \cdot 10^{-4}$ $\quad C_{t1} := 1.10 \cdot 10^{-1}$ $\quad C_{t0} := 6.56$

$$P := C_m \cdot freq^x \cdot B^y \cdot \left(\frac{C_{t0} - C_{t1} \cdot Temp + C_{t2} \cdot Temp^2}{1000} \right) \qquad P = 225.341$$

$Core\_loss := P \cdot Vol \cdot 10^{-3}$ $\quad Core\_loss = 11.861$

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$$Power := 7000 \qquad Power = 7 \times 10^3$$

$$I_{in} := \frac{Power}{V_{in}} \qquad I_{in} = 42.424 \qquad I_o := \frac{Power}{V_{out}} \qquad I_o = 250$$

$$I_{circ} := \left(\frac{Tp - 2 \cdot t_{on}}{Tp}\right) \cdot \frac{I_o}{2} \qquad I_{circ} = 15.758 \qquad I_{sec} := \left(\frac{I_o}{2} \cdot \sqrt{D_{max} \cdot 2}\right)$$

$$I_{secy} := I_{sec} + I_{circ} \qquad I_{secy} = 132.613 \qquad \frac{I_o}{2} = 125$$

$$I_{pri\_rms} := \left(\frac{I_o}{2} \cdot \sqrt{D_{max} \cdot 2}\right) \cdot \frac{N_s}{N_p} \qquad I_{pri\_rms} = 46.742$$

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$$\Delta ripple := 0.33 \cdot I_o \qquad \Delta ripple = 82.5 \qquad \text{~33\% ripple current}$$

$$I_{secy\_rms} := I_{sec} + I_{circ} + \frac{\Delta ripple}{3} \qquad I_{secy\_rms} = 160.113$$

$$I_{secy\_pk} := I_{sec} + I_{circ} + \frac{\Delta ripple}{2} \qquad I_{secy\_pk} = 173.863$$

$$I_{pri\_pk} := \frac{I_{pri\_rms}}{\sqrt{D_{max} \cdot 2}} + \frac{N_s}{N_p} \cdot I_{circ} + \frac{N_s}{N_p} \cdot \frac{\Delta ripple}{2} \qquad I_{pri\_pk} = 72.803$$

$$I_{pri\_rms} := \left(\frac{I_o}{2} \cdot \sqrt{D_{max} \cdot 2}\right) \cdot \frac{N_s}{N_p} + \frac{N_s}{N_p} \cdot I_{circ} + \frac{N_s}{N_p} \cdot \frac{\Delta ripple}{3} \qquad I_{pri\_rms} = 64.045$$

$Sec\_DCR := .0003 \quad Sec\_loss := \left[\left(I_{secy\_rms}\right)^2 \cdot Sec\_DCR\right] \quad Sec\_loss = 7.691$

$Pri\_DCR := .0025 \quad Pri\_loss := \left(\left(I_{pri\_rms}\right)\right)^2 \cdot Pri\_DCR \quad Pri\_loss = 10.255$

$Total\_Loss := Sec\_loss + Pri\_loss + Core\_loss \quad Total\_Loss = 29.807$

$Cu\_Loss := Sec\_loss + Pri\_loss \quad Cu\_Loss = 17.945 \quad Core\_loss = 11.861$

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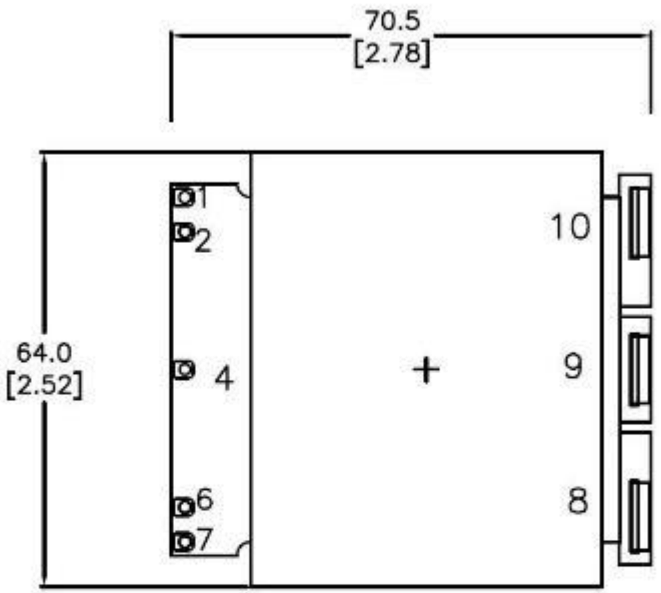

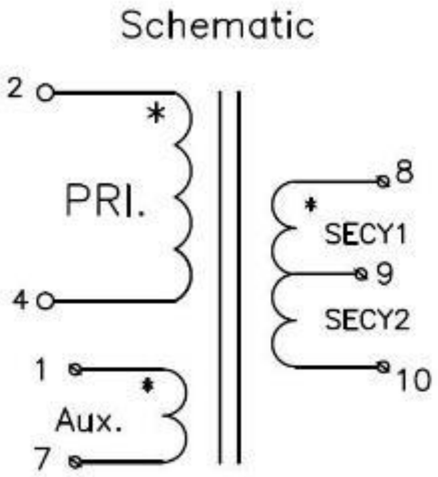

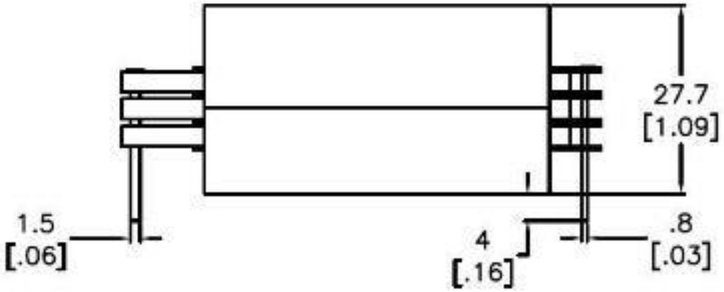

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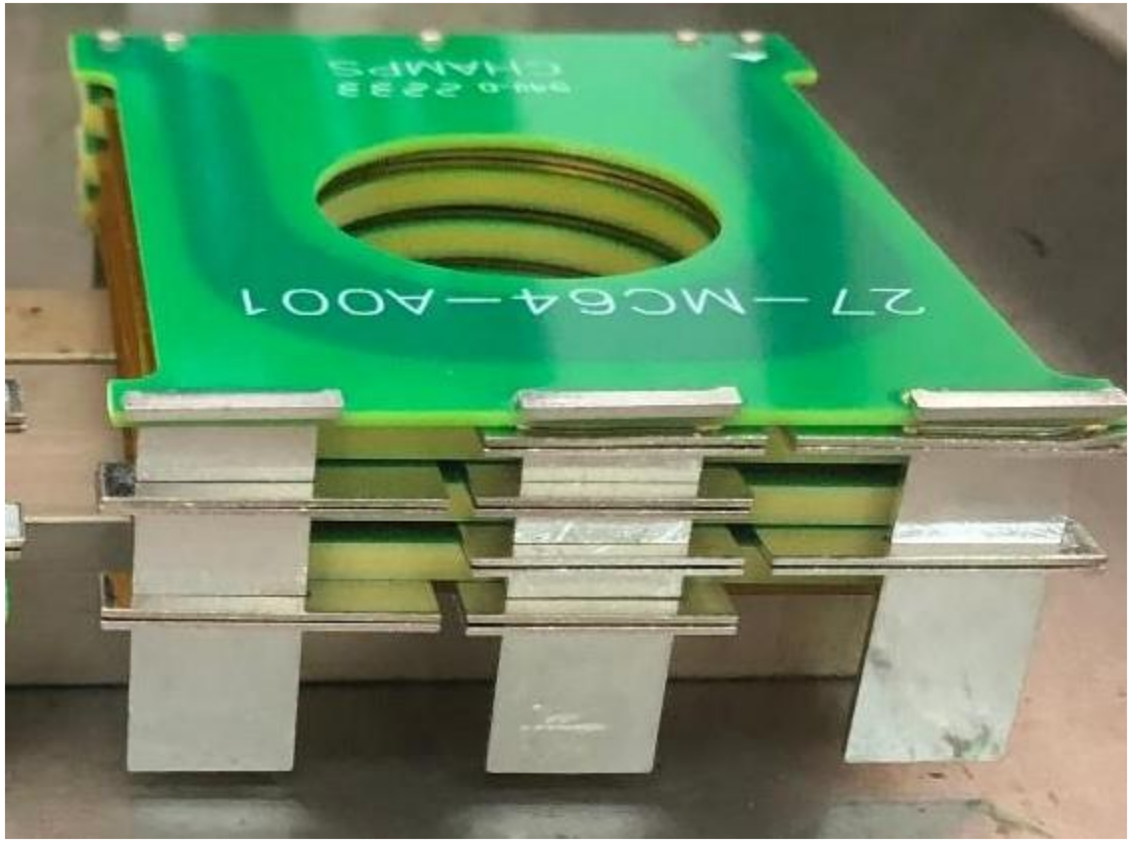
Transf. Stack: View Sec’y Terminals



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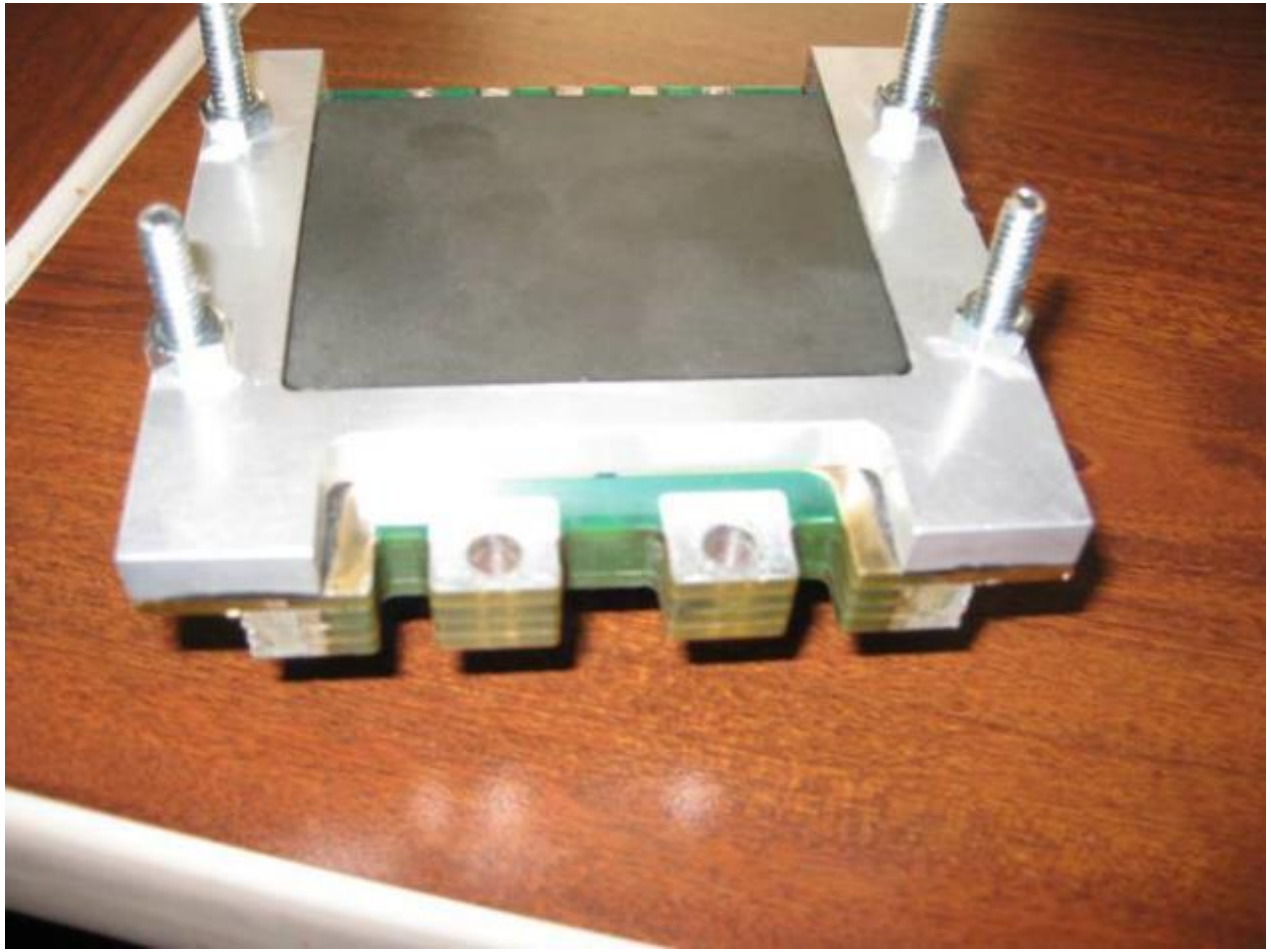
Aggressive Thermal Solution



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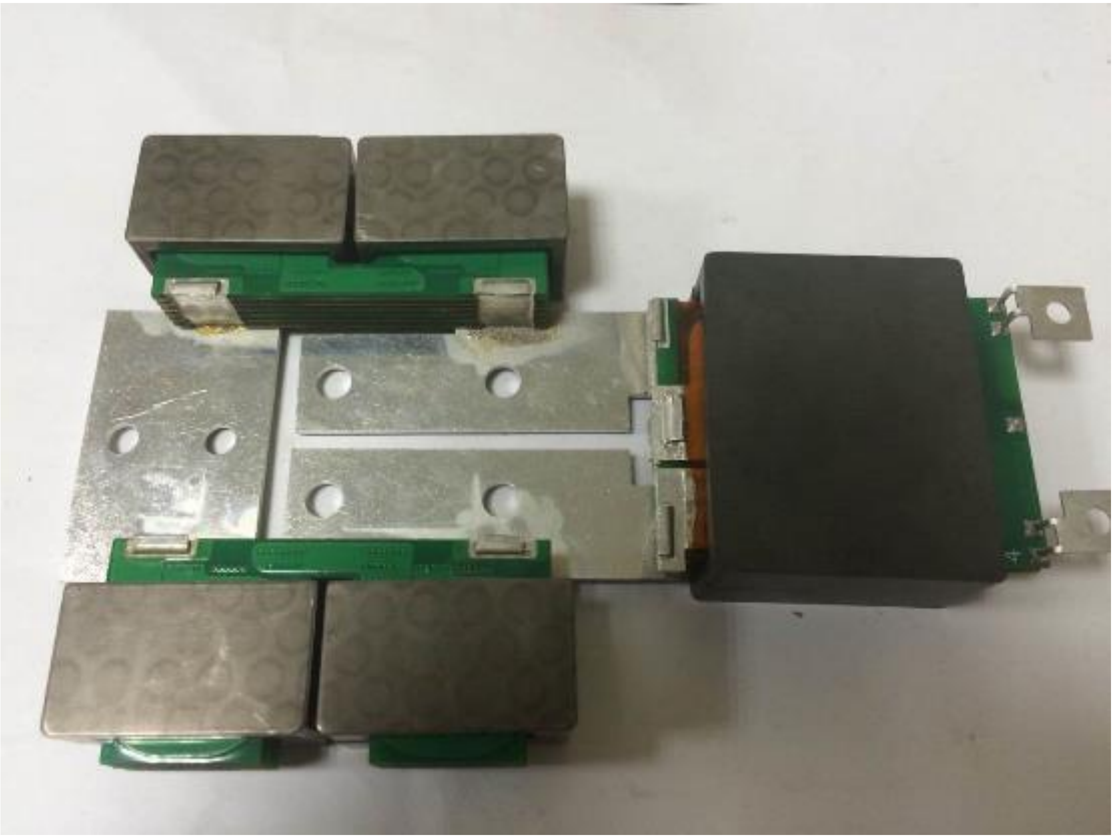
Distributed Thermal Solution



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Output Inductor Calculations

$$D_{min} := \frac{V_{out}}{V_{inmax}} \cdot \frac{N_p}{N_s} \cdot 1 \cdot Reg \qquad D_{min} = 0.225 \qquad t_{onmin} := \frac{D_{min}}{1} \cdot Tp \qquad t_{onmin} = 3.004 \times 10^{-6}$$

$$D_{min} \cdot 2 = 45.063\,\% \qquad t_{offmax} := Tp - t_{onmin} \qquad t_{offmax} = 1.033 \times 10^{-5}$$

$$V_{pk} := \left(V_{inmax} \cdot \frac{N_s}{N_p} \right) \qquad V_{pk} = 128 \qquad V_{inductor} := \frac{V_{pk}}{1} - V_{out} \qquad V_{inductor} = 100$$

$$I_{min} := I_o \cdot .33 \qquad I_{min} = 82.5 \qquad Lo_{min} := \frac{\left(V_{inductor}\right) \cdot t_{onmin}}{I_{min}} \qquad Lo_{min} = 3.641 \times 10^{-6}$$

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$L_o := 3.6 \cdot 10^{-6}$ $\Delta I := \frac{V_{inductor} \cdot t_{onmin}}{L_o}$ $\Delta I = 83.449$ $\frac{\Delta I}{I_o} = 0.334$

$L_{calc} := \frac{\left[V_{out} \cdot \left(1 - D_{min}\right)\right]}{\Delta I \cdot freq}$ $L_{calc} = 3.466 \times 10^{-6}$

$\Delta I\_off := \frac{V_{out} \cdot t_{offmax}}{L_o}$ $\Delta I\_off = 80.338$ $\frac{\Delta I\_off}{I_o} = 0.321$

$Inductor\_DCR := .00045$ $I_{rms} := \frac{I_o}{2} + \frac{\Delta I}{3}$ $I_{rms} = 152.816$

$Inductor\_loss := \left(I_{rms}\right)^2 \cdot Inductor\_DCR$ $Inductor\_loss = 10.509$

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$D_{min} = 0.225$ $L_o = 3.6 \times 10^{-6}$ $I_o = 250$

$D_t := D_{min}$ $N_t := \frac{N_p}{N_s}$ $N_t = 2.5$

$$\Delta I_L := \frac{\frac{V_{inmax}}{N_t} - V_{out}}{L_o} \cdot \frac{D_t}{freq}$$ $\Delta I_L = 83.449$ Peak Current for each individual inductor

$$\Delta I_L := \frac{V_{inmax} \cdot D_t - (D_t \cdot N_t \cdot V_{out})}{freq \cdot N_t \cdot L_o}$$ $\Delta I_L = 83.449$ $\frac{\Delta I_L}{I_o} = 0.334$

Source: Current Doubler Rectifier Offers Ripple Current Cancellation

TI Application Note SLUA323 Steve Mappus || https://www.ti.com/lit/an/slua323/slua323.pdf

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$$D_{min} = 0.225 \qquad L_o = 3.6 \times 10^{-6} \qquad I_o = 250$$

$$D_t := D_{min} \qquad N_t := \frac{N_p}{N_s} \qquad N_t = 2.5$$

$$\Delta I_{out} := \frac{V_{inmax} \cdot D_t - \left(2 \cdot D_t \cdot N_t \cdot V_{out}\right)}{freq \cdot N_t \cdot L_o} \qquad \Delta I_{out} = 60.083 \qquad \frac{\Delta I_{out}}{I_o} = 0.24$$

$$K := \frac{1 - D_t \cdot 2}{1 - \frac{D_t \cdot 2}{2}} \qquad K = 0.709$$

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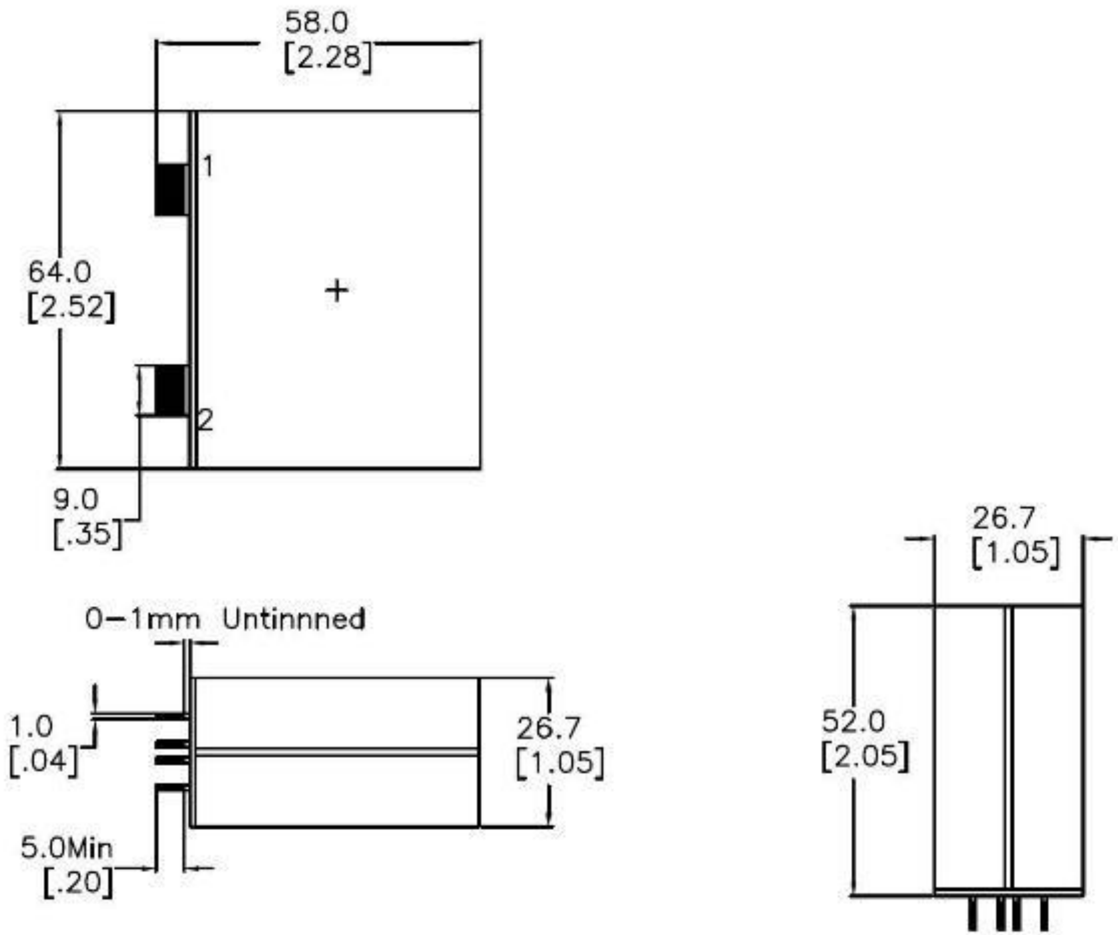
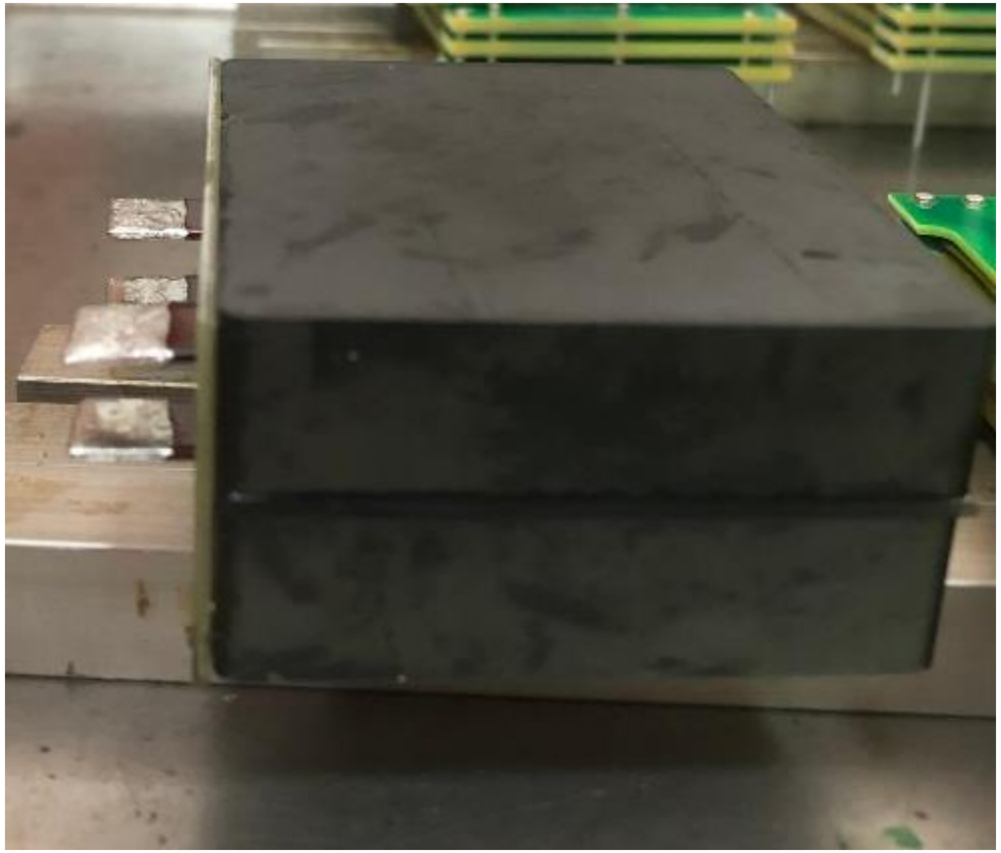
Output Inductor Spec



Output Inductors



3D Composite Design