Flyback Continuous mode – Planar Transformer Design Tutorial

An Industry Session at APEC 2020

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Payton America Inc.
Planar Technology

The Same Physics - used in an innovative way which results in:
Tremendous decrease in size/volume
Incredible weight reduction
Very High efficiency - 98% typical
Excellent parameter repeatability and consistency
Operating frequency range 50 kHZ – 5 MHZ
Unique safety solution.
Decrease inner temperature of Power Supply
Advantages of the Planar Technology

- High power density
- High reliability solution
- Consistency & Parameter Repeatability
- Easy to cool - Flat shape connected to a heat-sink
- High efficiency
- Ease of handling high current, up-to 1000A
Planar Technology basic materials

Basic materials are copper, insulators, cores and bobbins

• Copper stampings from 0.2-1mm is used for high current winding. Results in low losses, good thermal conductivity and perfect for high frequency
• ML PCB, up to 20 layers, up to 6oz copper (mostly 3). Allow high number of turns, PCB reliable technology and production stability
Planar Technology basic materials

- Double side pcb, Used as base plates and for low current application. same advantages as the ML.
- Insulators- Mostly stamped Polyimide and Nomex depends on the insulation requirements.

These materials allow consistent production between lots and high reliability products.
Planar Transformer Structure

- Ferrite
- Bobbin (Optional)
- Insulators
- Conductors
- Ferrite
Flat Pre-Tooled Winding

- **Secondary Winding**
- **Primary Winding**
- **CORE**

**Conventional transformer geometry**

- **Secondary winding**
- **Primary winding**

**Planar transformer geometry**
Proposed Specifications:

Pout=100 Watts
Vo=5V
Iout=20A
F=200kHz
Input=18-36Vdc
Tamb= -55C to +80C
Tsurface=90C
Topology=Continuous Flyback
Current Waveforms of a Continuous Flyback

- $I_{pricpr}$
- $I_{pri}$
- $I_{pk}$
- $I_{sec}$

Parameters:
- $ton$
- $t$
Turns Ratio Calculation

Set Dmax at .65

\[
\frac{N_p}{N_{sec}} = \frac{V_{inmin} - V_{sat}}{V_{out} + V_{diode}} \cdot \frac{D_{max}}{1 - D_{max}} = \frac{18 - .5}{5 + .5} \cdot \frac{.65}{1 - .65} = 5.91
\]

Set \(\frac{N_p}{N_{sec}} = 6\)

\[
D_{max} = \frac{1}{1 + \left(\frac{V_{inmin} - V_{sat}}{(V_{out} + V_{diode}) \cdot \frac{N_p}{N_s}}\right)} = \frac{1}{1 + \frac{18 - .5}{(5 + .5) \cdot 6}} = .65
\]
\[ I_{prictr} = \frac{P_{out}}{(Eff \times (Vin_{min} - V_{sat}) \times D_{max})} = \frac{100}{.87 \times (18 - .5) \times .65} = 10.10 \text{ Amps} \]

\[ I_{pirms} = I_{prictr} \times \sqrt{D_{max}} = 10.10 \times \sqrt{.65} = 8.14 \text{ Amps} \]

\[ I_{pk} = I_{prictr} + \frac{I_{priripple}}{2} = 10.10 + \frac{2.02}{2} = 11.11 \text{ Amps} \quad \text{(needed for B_{max})} \]

\[ I_{screms} = \frac{I_{dc_{sec}}}{\sqrt{(1 - D_{max})}} = \frac{20}{\sqrt{(1 - .65)}} = 33.9 \text{ Amps} \]

\[ I_{priripple} = \frac{2 \times P_{min}}{Eff \times (Vin_{min} - V_{sat}) \times D_{max}} = \frac{2 \times 10}{.87 \times (18 - .5) \times .65} = 2.02 \text{ Amps} \]

With 10% min load.
\[ L_p = \frac{(V_{\text{in min}} - V_{\text{sat}}) \cdot D_{\text{max}}}{F \cdot I_{\text{ripple}}} = \frac{(18 - 0.5) \cdot 0.65}{200,000 \cdot 2.02} = 28 \mu H \]

\[ A_l = \frac{L_p}{N_p^2} = \frac{28 \mu H}{12^2} = 194 \, nH/\text{turn}^2 \quad (A_l \text{ is needed to calculate the effective permeability } \mu_e) \]
One **gauss** is defined as one maxwell per square centimeter. The cgs system has been superseded by the International System of Units (SI), which uses the **tesla** (symbol T) as the unit of magnetic flux density. One **gauss** equals $1 \times 10^{-4}$ **tesla** (100 μT), so 1 **tesla** = 10,000 **gauss**.

$$B_{\text{max}} = \frac{L_p I_{\text{peak}}}{N_p A_e} = \frac{28 \mu\text{H} \times 11.11}{12 \times 130 \times 10^{-6}} = 0.199 \text{ T}$$

Core E32 with Amin=130$mm^2$ and Le=41.4mm. R material with Bmax at 130C of .3T.

Need 12T then Bmax=.199 T Perfect !!
With 6T Bmax=.398T which is a bit high

So the transformer will be T130(E32)-12-2/28uH
Description
Payton SIZE 130 provides a planar solution for low to medium power applications such as providing high efficiency, low EMI, excellent repeatability, low profile and weight with an operating temperature range of -40°C to +130°C.

1. Transformer Application

<table>
<thead>
<tr>
<th>POWER CAPACITY</th>
<th>DIMENSIONS (mm)</th>
<th>TYPICAL WEIGHT</th>
<th>DIELECTRIC ISOLATION</th>
<th>OPERATING VOLTAGE</th>
<th>OPERATING CURRENT (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100W, Flyback CCM at 100 kHz</td>
<td>L = 37-60, W = 34, H = 8-30</td>
<td>60 gr.</td>
<td>Up to 4k Vrms</td>
<td>500 Vpeak max.</td>
<td>100 A max.</td>
</tr>
</tbody>
</table>

Typical efficiency: 97-99%
Recommended frequency range: 100 kHz – 2.5 MHz.

Topologies:
Full bridge; Half bridge; Push-Pull; Forward; Flyback; Boost; Buck; Resonant topologies (in order of preference).

Mounting Options: a. Horizontal, b. Vertical

2. Inductor Application

<table>
<thead>
<tr>
<th>STANDARD ( L ) (nH/µm)</th>
<th>1600</th>
<th>1000</th>
<th>630</th>
<th>400</th>
<th>315</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPICAL VALUE OF MAX. Amper Turns</td>
<td>22</td>
<td>40</td>
<td>67</td>
<td>106</td>
<td>132</td>
<td>243</td>
</tr>
</tbody>
</table>

\( L \) values not listed are available upon request.

3. Typical Thermal Impedance For Different Cooling Conditions

<table>
<thead>
<tr>
<th>NATURAL COOLING (Hot Spot - Air)</th>
<th>BLOWING AIR 3m/sec (Hot Spot - Air)</th>
<th>ONE SIDE HEATSINK (Hot Spot - Heatsink)</th>
<th>TWO SIDES HEATSINK (Hot Spot - Heatsink)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14°C/W</td>
<td>9°C/W</td>
<td>4.5°C/W</td>
<td>2.3°C/W</td>
</tr>
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</table>
## Planar Core Data

### (ungapped)

### Power Materials

<table>
<thead>
<tr>
<th>PART</th>
<th>COMB.</th>
<th>P</th>
<th>R</th>
<th>F*</th>
<th>J</th>
<th>W</th>
<th>Lp (mm)</th>
<th>Aρ (mm²)</th>
<th>Amin (mm²)</th>
<th>Amax (mm²)</th>
<th>Vρ (mm³)</th>
<th>Vw</th>
<th>Core Weight (grams per core)</th>
<th>Robin Window Area (cm²)</th>
<th>VwA (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0_41425EC</td>
<td>EE</td>
<td>1,196</td>
<td>1,139</td>
<td>1,765</td>
<td>2,650</td>
<td>4,260</td>
<td>16.7</td>
<td>14.7</td>
<td>14.7</td>
<td>244</td>
<td>1.2</td>
<td>0.064</td>
<td>0.009</td>
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<tr>
<td>C_41434EC*</td>
<td>EE</td>
<td>1,089</td>
<td>995</td>
<td>1,563</td>
<td>2,140</td>
<td>3,420</td>
<td>20.7</td>
<td>14.6</td>
<td>16.6</td>
<td>303.9</td>
<td>1.5</td>
<td>0.128</td>
<td>0.01</td>
<td></td>
<td></td>
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<tr>
<td>C_41434IC</td>
<td>EE</td>
<td>1,185</td>
<td>1,124</td>
<td>1,749</td>
<td>2,680</td>
<td>-</td>
<td>16.4</td>
<td>14.2</td>
<td>11.4</td>
<td>250</td>
<td>1.2</td>
<td>0.064</td>
<td>0.009</td>
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<tr>
<td>C_41805EC*</td>
<td>EE</td>
<td>2,520</td>
<td>2,433</td>
<td>3,880</td>
<td>5,470</td>
<td>-</td>
<td>24.2</td>
<td>40.1</td>
<td>39.9</td>
<td>972</td>
<td>4.9</td>
<td>0.16</td>
<td>0.06</td>
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<td>2,705</td>
<td>4,241</td>
<td>6,850</td>
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<td>20.3</td>
<td>39.5</td>
<td>35.9</td>
<td>830</td>
<td>4.1</td>
<td>0.08</td>
<td>0.03</td>
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<tr>
<td>F_41805EC*</td>
<td>EE</td>
<td>2,573</td>
<td>2,433</td>
<td>3,853</td>
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<td>-</td>
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<td>40.1</td>
<td>39.9</td>
<td>972</td>
<td>-</td>
<td>-</td>
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<tr>
<td>F_41805IC</td>
<td>EE</td>
<td>2,878</td>
<td>2,731</td>
<td>4,278</td>
<td>-</td>
<td>-</td>
<td>20.3</td>
<td>40.1</td>
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<td>813</td>
<td>-</td>
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<td>C_42107EC</td>
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<td>2,769</td>
<td>2,586</td>
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<td>8,260</td>
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<td>160</td>
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<td>C_42216EC*</td>
<td>EE</td>
<td>4,040</td>
<td>3,800</td>
<td>6,131</td>
<td>8,640</td>
<td>13,300</td>
<td>32.3</td>
<td>76</td>
<td>73.1</td>
<td>2,451</td>
<td>-</td>
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<tr>
<td>C_42216IC</td>
<td>EE</td>
<td>4,880</td>
<td>4,610</td>
<td>7,327</td>
<td>10,750</td>
<td>-</td>
<td>26.1</td>
<td>80.4</td>
<td>72.5</td>
<td>1,100</td>
<td>10.4</td>
<td>0.15</td>
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<td>EE</td>
<td>5,673</td>
<td>5,318</td>
<td>8,672</td>
<td>10,930</td>
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<td>130</td>
<td>130</td>
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<td>26</td>
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<tr>
<td>F_43208IC</td>
<td>EE</td>
<td>4,422</td>
<td>4,036</td>
<td>9,760</td>
<td>12,892</td>
<td>-</td>
<td>35.1</td>
<td>130</td>
<td>130</td>
<td>3,560</td>
<td>22</td>
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<td>0.33</td>
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<tr>
<td>0_43618EC</td>
<td>EE</td>
<td>5,800</td>
<td>5,435</td>
<td>8,887</td>
<td>-</td>
<td>-</td>
<td>42.4</td>
<td>135</td>
<td>135</td>
<td>5,750</td>
<td>28</td>
<td>0.412</td>
<td>0.55</td>
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<tr>
<td>0_43618IC</td>
<td>EE</td>
<td>4,382</td>
<td>5,991</td>
<td>9,725</td>
<td>12,760</td>
<td>21,600</td>
<td>37.4</td>
<td>185</td>
<td>185</td>
<td>5,040</td>
<td>25</td>
<td>0.204</td>
<td>0.27</td>
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<tr>
<td>F_43808EC</td>
<td>EE</td>
<td>7,006</td>
<td>6,548</td>
<td>10,784</td>
<td>-</td>
<td>-</td>
<td>52.4</td>
<td>194</td>
<td>194</td>
<td>10,200</td>
<td>50.9</td>
<td>0.813</td>
<td>1.56</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* F material nominal ±25%

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**Available Hardware**

- C_41434IC
- C_41805IC
- C_42216IC

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**Mag-Inc.com**

**11.19**

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**Payton Planar**

Innovation • Design • Performance
R Material

\[ B = 2300 \pm 25\% \]

**Permeability vs. Temperature**

- 6000 Gauss
- 1000 Gauss

**Core Loss vs. Temperature**

**Core Loss vs. Flux Density**

**Permeability vs. Flux Density**

**Flux Density vs. Temperature**

See Page 3.11 for B-Hl Data
\[ \mu e = \frac{Al \cdot \left( \frac{le}{Ae} \right)}{1.257} = \frac{194 \cdot \left( \frac{41.4}{130} \right)}{1.257} = 49 \]

\[ Gap = \frac{\mu_i - \mu e}{\mu_e \cdot \mu_i} \cdot Le = \frac{2300 - 49}{2300 \cdot 49} \cdot 41.4 = .827\text{mm} \]

I use 20% higher to compensate for the coefficient of fringing then the gap will be .9924 and I will use 1mm. The ratio of the total flux produced to the useful flux set up in the air gap of the magnetic circuit is called a leakage coefficient or leakage factor.
CoreLoss = $a \cdot f^c \cdot B^d$

\[
= 0.036 \cdot 200^{1.64} \cdot 0.18^{2.68} = 2.16\, mW/cm^3
\]

\(F\) (kHz)

\(B = \text{ac peak flux density (kG)}\)

\[
B = \frac{B_{\text{max}} - B_{\text{min}}}{2} = \frac{199 - 163}{2} = 0.018\, T \quad (180\, \text{gauss})
\]

\(B_{\text{min}} = \frac{I_p \cdot I_{\text{pmin}}}{N_p \cdot A_e} = \frac{28uH \cdot 9.09}{12 \cdot 130 \cdot 10^{-6}} = 0.163\, T \quad (1630\, \text{gauss})
\]

\[
I_{\text{pmin}} = I_{\text{prictr}} - \frac{I_{\text{priripple}}}{2} = 10.10 - \frac{2.02}{2} = 9.09\, \text{Amps}
\]

\(P_{\text{core}} = V_e \cdot \text{CoreLoss} = 5 \cdot 2.16 = 10.79\, mW \quad \text{(at 100C core temp)}\)
12:2 construction using double interleaving with $M = 2^2 = 4$

Leakage inductance depends on the winding arrangements and is according to Snelling.

M is the number of section interfaces and is in the denominator of the equation.

3T Primary 1.96mOhms, 15mil with skin coefficient of 1.712 at 200kHz
1T Secondary .61mOhms, 15mil
3T + 3T Primary
1T Secondary
3T Primary
Calculations of dcr and acr for primary and secondary windings.

\[
R_{dcpri} \text{ (12T)} = 1.96 \times 4 = 7.84 \text{mOhms} \\
R_{acprim} = R_{dcpri} \times K_{skin} \times K_{correction} \text{ (at 120C hotpsot)} \\
R_{acpri} = 7.84 \times 1.712 \times 1.35 = 18.12 \text{mOhms} \\
\]

\[
R_{dcsec} \text{ (2T)} = .61 \times 2 = 1.22 \text{mOhms} \\
R_{acsec} = 1.22 \times 1.712 \times 1.35 = 2.82 \text{mOhms} \\
\]
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Skin depth (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Hz</td>
<td>9220</td>
</tr>
<tr>
<td>60 Hz</td>
<td>8420</td>
</tr>
<tr>
<td>10 kHz</td>
<td>652</td>
</tr>
<tr>
<td>100 kHz</td>
<td>206</td>
</tr>
<tr>
<td>1 MHz</td>
<td>65.2</td>
</tr>
<tr>
<td>10 MHz</td>
<td>20.6</td>
</tr>
<tr>
<td>100 MHz</td>
<td>6.52</td>
</tr>
<tr>
<td>1 GHz</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Skin depth is due to the circulating eddy currents (arising from a changing H field) cancelling the current flow in the center of a conductor and reinforcing it in the skin.

Info taken from Wikipedia
In a conductor carrying switching current, if currents are flowing through one or more other nearby conductors, such as within a closely wound coil of wire, the distribution of current within the first conductor will be constrained to smaller regions. The resulting current current crowding is termed the **proximity effect**. This crowding gives an increase in the **effective resistance** of the circuit, which increases with frequency.

Excellent reference:

*Proximity Loss in Magnetics Windings*

By Dr. Ray Ridley
Copper Losses

\[ P_{cop} = R_{acpri} * I^2_{prims} + R_{acsec} * I^2_{secrms} \]

\[ P_{cop} = 18.12m * 8.14^2 + 2.82m * 33.9^2 = 1.2 + 3.24 = 4.44 \text{ Watts} \]

\[ LI \ (1\text{turn size 130}) = 3.5^{nH} \text{ per turn}^2 = 0.5uH \]

\[ P_{react} = 6.17 \text{ watts} \text{ (empirical calculation)} \]

For 100 Watt transformer the proximity losses are about 4 times less than the reactive losses.

\[ P_{proximity} = \frac{P_{react}}{4} = 1.54 \text{ watts} \]

\[ \text{Total Losses} = P_{cop} + P_{pro} + P_{core} = 4.44 + 1.54 + 0.01 = 5.99 \text{ Watts} \]

For size 130 with one side heatsink the thermal impedance is \( \frac{5^\circ C}{W} \)

\[ \text{Temp. rise} = 6 \times 5 = 30^\circ C \]
Core Loss Equation

Included on pages 3.4-3.9 are material characteristics for the various Magnetics power and inductor materials. For computer programming purposes, the core loss curves can be represented by the equation below.

The factors indicated in the chart are split into discrete frequency ranges, so that the equation offers a close approximation to the core loss curves on the above pages.

CORE LOSS EQUATION: \( P = a + b + c + d \)

- \( P \) is in mW/cm²
- \( B \) is in kG
- \( f \) is in kHz

<table>
<thead>
<tr>
<th>Material</th>
<th>( f \leq 100) kHz</th>
<th>( 100) kHz (-) ( 500) kHz</th>
<th>( f = 500) kHz</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
<th>( d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Material</td>
<td>( f = 100) kHz</td>
<td>0.074</td>
<td>1.43</td>
<td>2.85</td>
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<tr>
<td></td>
<td>( f = 500) kHz</td>
<td>0.014</td>
<td>1.84</td>
<td>2.28</td>
<td></td>
<td></td>
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<tr>
<td>P Material</td>
<td>( f = 100) kHz</td>
<td>0.158</td>
<td>1.36</td>
<td>2.86</td>
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<tr>
<td></td>
<td>( 100) kHz (-) ( 500) kHz</td>
<td>0.0434</td>
<td>1.63</td>
<td>2.62</td>
<td></td>
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<tr>
<td></td>
<td>( f = 500) kHz</td>
<td>7.26 (-) ( 10^{-7})</td>
<td>2.47</td>
<td>2.54</td>
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<td>F Material</td>
<td>( f = 10) kHz</td>
<td>0.790</td>
<td>1.06</td>
<td>2.85</td>
<td></td>
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<tr>
<td></td>
<td>( 10) kHz (-) ( 100) kHz</td>
<td>0.0717</td>
<td>1.72</td>
<td>2.66</td>
<td></td>
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<td></td>
<td>( 100) kHz (-) ( 500) kHz</td>
<td>0.0573</td>
<td>1.66</td>
<td>2.68</td>
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<td></td>
<td>( f = 500) kHz</td>
<td>0.0126</td>
<td>1.88</td>
<td>2.29</td>
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<td>J Material</td>
<td>( f = 20) kHz</td>
<td>0.245</td>
<td>1.39</td>
<td>2.50</td>
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<tr>
<td></td>
<td>( f = 20) kHz</td>
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<td>2.42</td>
<td>2.50</td>
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<td>W Material</td>
<td>( f = 20) kHz</td>
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<td>1.26</td>
<td>2.60</td>
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<td></td>
<td>( f = 20) kHz</td>
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