SWITCHING POWER SUPPLY DESIGN:
CONTINUOUS MODE
FLYBACK CONVERTER

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Typical Flyback power supply:

Notes:
Write down the power supply requirements on:

Get the results on:

This Mathcad file helps the calculation of the external components of a typical continuous mode switching power supply.

Input voltage:
- Minimum input voltage: \( V_{i\text{min}} := 90 \text{ volt} \)
- Maximum input voltage: \( V_{i\text{max}} := 460 \text{ volt} \)
- Nominal input voltage: \( V_{i\text{nom}} := 300 \text{ volt} \)

Output:
- Nominal output voltage, maximum output ripple, minimum output current, maximum output current

\[
\begin{align*}
V_{o1} &:= 108 \text{ volt} & V_{rp1} &:= 1000 \text{ mV} & I_{o1\text{min}} &:= 0.1 \text{ amp} & I_{o1\text{max}} &:= 1.0 \text{ amp} \\
V_{o2} &:= 0 \text{ volt} & V_{rp2} &:= 120 \text{ mV} & I_{o2\text{min}} &:= 0.000 \text{ amp} & I_{o2\text{max}} &:= 0.000 \text{ amp} \\
V_{d\text{fw}} &:= 0.7 \text{ volt} & \text{( diode's forward drop voltage)}
\end{align*}
\]

\[
\begin{align*}
Po_{\text{min}} &:= (V_{o1} + V_{d\text{fw}}) \cdot I_{o1\text{min}} + (V_{o2} + V_{d\text{fw}}) \cdot I_{o2\text{min}} \\
Po_{\text{max}} &:= (V_{o1} + V_{d\text{fw}}) \cdot I_{o1\text{max}} + (V_{o2} + V_{d\text{fw}}) \cdot I_{o2\text{max}}
\end{align*}
\]

\[
\begin{align*}
Po_{\text{min}} &:= 10.87 \text{ watt} & Po_{\text{max}} &:= 108.7 \text{ watt}
\end{align*}
\]
- Switching Frequency: \( f_{sw} := 100 \cdot \text{kHz} \quad T := \frac{1}{f_{sw}} \quad T = 10 \cdot \mu\text{sec} \)

- Transformer’s Efficiency: \( \eta := 0.90 \) (Guessed value)

- Maximum drop voltage across the switching mosfet during the on time:

- On resistance of the Mosfet: \( R_{ds_{on}} := 0.18 \cdot \text{ohm} \)

\[
V_{ds_{on}} := \frac{P_{o_{max}}}{\eta \cdot V_{i_{min}}} - R_{ds_{on}} \quad V_{ds_{on}} = 0.24 \cdot \text{volt}
\]

1) Define Primary/secondary turns ratio: \( N_{ps1} \)

Primary/secondary turns ratio can be selected as compromise between maximum voltage across the switching mosfet and desired max.-min. duty cycle.

- Nominal desired on Duty Cycle: \( D_{nom} := 0.24 \)

\[
N_{ps1} := \left( \frac{V_{i_{nom}} - V_{ds_{on}}}{Vo_1 + V_{d_{lw}}} \right) \frac{D_{nom}}{1 - D_{nom}} \quad N_{ps1} = 0.9
\]

The calculated turns ratio can be modified to optimise the windings

- Flyback voltage across the mutual inductance during the off time: \( V_{fm} \)

\[
V_{fm} := N_{ps1} \cdot (Vo_1 + V_{d_{lw}}) \quad V_{fm} = 94.66 \cdot \text{volt}
\]

- Maximum voltage across the switching-mosfet:

\[
F_{spike} := 0.15 \quad V_{ds_{max}} := (F_{spike} + 1) \cdot (V_{i_{max}} + V_{fm}) \quad V_{ds_{max}} = 637.86 \cdot \text{volt}
\]

Safe factor (assume spikes of 20-30% of Vdc)

To reduce the maximum voltage across the switching mosfet reduce \( N_{ps} \) turns ratio by reducing the desired on-duty cycle

- Slave output turns ratio: \( N_{ps2} := \frac{V_{fm}}{Vo_2 + V_{d_{lw}}} \quad N_{ps2} = 135.2 \)

2) Maximum and minimum duty cycle: \( D_{max} \) and \( D_{min} \)

To maintain the continuous mode of operation the dead time has to be equal zero \((T_{on} + T_{off} = T)\), and to reset the core every cycle, the average voltage on the primary inductance must be equal zero: \(( V_i - V_{ds_{on}} ) \cdot T_{on} = ( V_o + V_{d_{off}} ) \cdot T_{off} \), where \( T_{off} \) is equal to \((T - T_{on})\)

\[
T_{on_{max}} := \frac{V_{fm} \cdot T}{(V_{i_{min}} - V_{ds_{on}}) + V_{fm}} \quad T_{on_{max}} = 5.13 \cdot \mu\text{sec}
\]

\[
T_{on_{min}} := \frac{V_{fm} \cdot T}{(V_{i_{max}} - V_{ds_{on}}) + V_{fm}} \quad T_{on_{min}} = 1.71 \cdot \mu\text{sec}
\]
3) Primary winding: Inductance, peak, AC, RMS current

In continuous mode the duty cycle changes with a change of input voltage. An increase of output current, will temporarily increase the duty cycle until the average primary and secondary currents increase.

- Primary average current:

\[ I_{p_{cs}} := \frac{P_{o_{max}}}{(V_{i_{min}} - V_{d_{on}}) \eta \cdot D_{max}} \]

\[ I_{p_{cs}} = 2.62 \text{ amp} \]

There are several criteria to select the primary and secondary inductances, following are explained two different solutions: the first one is to select the primary inductance in order to ensure continuous mode of operation from full load to minimum load. (about 1/10-1/20 of the maximum load). (3-a), The second alternative criteria, is to calculate primary and secondary inductances by defining maximum secondary ripple current. (3-b)

3-a) Select primary inductance for continuous mode of operation at minimum load:

During the transition from discontinuous to continuous mode, the peak primary current it’s about double the central average current \( I_{p_{cs(min)}} \). In order to maintain continuous mode at minimum load the maximum ramp amplitude has to be twice the minimum average current.

- Ramp amplitude:

\[ \Delta I_{p} := \frac{2 \cdot P_{o_{min}}}{(V_{i_{min}} - V_{d_{on}}) \eta \cdot D_{max}} \]

\[ \Delta I_{p} = 0.52 \text{ amp} \]
3-b) Primary and secondary inductance for a maximum defined secondary peak to peak ripple current:

AC core losses, AC winding losses, and output ripple current are directly proportional to the current ramp amplitude of the primary and secondaries windings. Therefore in high current application, AC ripple currents could have a predominant role on the overall performance of the converter, a good compromise between transformer’s size and AC currents can be obtained by selecting the most appropriate secondary ripple current:

- Desired secondary ripple current: \( \Delta I_s % := \frac{\text{maximum value}}{\text{average}} \) (maximum value / average)

\[
I_{s1cs} := \frac{I_{o1max}}{1 - D_{max}}
\]

\[
I_{s1cs} = 2.05 \cdot \text{amp}
\]

- Ramp amplitude:

\[
\Delta I_{s1b} := I_{s1cs} \cdot \Delta I_s %
\]

\[
\Delta I_{s1b} = 0.47 \cdot \text{amp}
\]

- Secondary inductance:

\[
L_{s1b} := \frac{(V_{o1} + V_{d1w}) \cdot (T - T_{on\max})}{\Delta I_{s1b}}
\]

\[
L_{s1b} = 1.12 \times 10^3 \cdot \mu\text{H}
\]

- Primary inductance:

\[
L_{p0} := L_{s1b} \cdot N_{ps1}^2
\]

\[
L_{p0} = 849.02 \cdot \mu\text{H}
\]

- Ramp amplitude:

\[
\Delta I_{p} := \frac{(V_{min} - V_{ds_{on}}) \cdot T_{on\max}}{L_{p}}
\]

\[
\Delta I_{p} = 0.54 \cdot \text{amp}
\]

Select primary inductance (3-a) or (3-b):---->

\[
L_p := L_{p0}
\]

\[
L_p = 849.02 \cdot \mu\text{H}
\]

- Primary average current:

\[
I_{p_{cs}} := \frac{P_{o_{max}}}{(V_{min} - V_{ds_{on}}) \eta \cdot D_{max}}
\]

\[
I_{p_{cs}} = 2.62 \cdot \text{amp}
\]

- Primary peak current:

\[
I_{p_{pk}} := I_{p_{cs}} + \frac{\Delta I_{p}}{2}
\]

\[
I_{p_{pk}} = 2.89 \cdot \text{amp}
\]

- Primary RMS current:

\[
I_{p_{rms}} := \sqrt{D_{max} \left[ I_{p_{pk}} \left( I_{p_{cs}} - \frac{\Delta I_{p}}{2} \right) + \frac{1}{3} \left( I_{p_{pk}} - \left( I_{p_{cs}} - \frac{\Delta I_{p}}{2} \right) \right)^2 \right]}
\]

\[
I_{p_{rms}} = 1.88 \cdot \text{amp}
\]
- Primary DC current: \[ I_{pdc} := \frac{P_{omax}}{\eta (V_{min} - V_{ds_{on}})} \] \[ I_{pdc} = 1.35 \text{ amp} \]

- Primary AC(rms) current: \[ I_{pac} := \sqrt{I_{prms}^2 - I_{pdc}^2} \] \[ I_{pac} = 1.32 \text{ amp} \]

\[ Edt := V_{min} Ton_{max} \] \[ Edt = 4.62 \times 10^{-4} \text{ volt sec} \]

4) Secondary winding: Inductance, peak, AC, RMS current

- Master output:

  - Primary average current: \[ Is_{1pk} := \frac{Io_{1max}}{1 - D_{max}} \] \[ Is_{1cs} = 2.05 \text{ amp} \]

  - Secondary inductance : \[ Ls1 := \frac{Lp}{Nps1^2} \] \[ Ls1 = 1.12 \times 10^3 \mu\text{H} \]

  - Ramp amplitude: \[ \Delta Is1 := \frac{(Vo1 + Vd_{lw}) (T - Ton_{max})}{Ls1} \] \[ \Delta Is1 = 0.47 \text{ amp} \]

  - Secondary peak current: \[ Is_{1pk} := Is_{1cs} + \frac{\Delta Is1}{2} \] \[ Is_{1pk} = 2.29 \text{ amp} \]

- Secondary RMS current:

\[ Is_{1rms} := \sqrt{\left(1 - D_{max}\right) \left[ Is_{1pk} \left( Is_{1cs} - \frac{\Delta Is1}{2} \right) + \frac{1}{3} \left[ Is_{1pk} - \left( Is_{1cs} - \frac{\Delta Is1}{2} \right) \right]^2 \right]} \] \[ Is_{1rms} = 1.44 \text{ amp} \]

- Secondary AC current: \[ Is_{1ac} := \sqrt{Is_{1rms}^2 - Io_{1max}^2} \] \[ Is_{1ac} = 1.03 \text{ amp} \]

- First slave output:

  - Primary average current: \[ Is_{2cs} := \frac{Io_{2max}}{1 - D_{max}} \] \[ Is_{2cs} = 0 \text{ amp} \]

  - Secondary inductance : \[ Ls2 := \frac{Lp}{Nps2^2} \] \[ Ls2 = 0.05 \mu\text{H} \]

  - Ramp amplitude: \[ \Delta Is2 := \frac{(Vo2 + Vd_{lw}) (T - Ton_{max})}{Ls2} \] \[ \Delta Is2 = 73.38 \text{ amp} \]

  - Secondary peak current: \[ Is_{2pk} := Is_{2cs} + \frac{\Delta Is2}{2} \] \[ Is_{2pk} = 36.69 \text{ amp} \]

- Secondary RMS current:

\[ Is_{2rms} := \sqrt{\left(1 - D_{max}\right) \left[ Is_{2pk} \left( Is_{2cs} - \frac{\Delta Is2}{2} \right) + \frac{1}{3} \left[ Is_{2pk} - \left( Is_{2cs} - \frac{\Delta Is2}{2} \right) \right]^2 \right]} \]
- Secondary AC current: 
\[ I_{s2_{\text{ac}}} = \sqrt{I_{s2_{\text{rms}}}^2 - I_{o2_{\text{max}}}^2} \]

5) Maximum Stress across the output diodes: \( V_{\text{diode}} \)

- Maximum stress voltage on the cathode of diodes

\[ V_{\text{diode1}}_{\text{max}} := \frac{V_{i_{\text{max}}}}{N_{ps1}} + V_{o1} \]

\[ V_{\text{diode1}}_{\text{max}} = 636.22 \, \text{volt} \]

\[ V_{\text{diode2}}_{\text{max}} := \frac{V_{i_{\text{max}}}}{N_{ps2}} + V_{o2} \]

\[ V_{\text{diode2}}_{\text{max}} = 3.4 \, \text{volt} \]

Select a diode with \( V_{a-c} >> V_{\text{diode.max}} \), and ultra-fast switching diode

\[ P_{\text{diode1}}_{\text{max}} := I_{s1_{\text{rms}}} \cdot V_{d_{fw}} \cdot (1 - D_{\text{max}}) \]

\[ P_{\text{diode1}}_{\text{max}} = 0.49 \, \text{watt} \]

\[ P_{\text{diode2}}_{\text{max}} := I_{s2_{\text{rms}}} \cdot V_{d_{fw}} \cdot (1 - D_{\text{max}}) \]

\[ P_{\text{diode2}}_{\text{max}} = 5.04 \, \text{watt} \]

\[ P_{\text{diode tot}} := P_{\text{diode1}}_{\text{max}} + P_{\text{diode2}}_{\text{max}} \]

\[ P_{\text{diode tot}} = 5.52 \, \text{watt} \]

6) Output ripple Specifications and Output Capacitors

To meet the output ripple specifications the output capacitors have to meet two criterias:
- satisfy the standard capacitance definition: \( I_{s} = C \cdot \frac{dV}{dt} \) where \( t \) is the Toff time, \( V \) is 25% of the allowable output ripple.
- The Equivalent Series Resistance (ESR) of the capacitor has to provide less than 75% of the maximum output ripple. \( (V_{\text{ripple}} = dI \cdot \text{ESR}) \)

- Maximum outputs ripple:

\[ V_{\text{rp1}} = 1 \times 10^3 \, \text{mV} \quad V_{\text{rp2}} = 120 \, \text{mV} \]

- Minimum output capacitance:

\[ C_{o1} := \Delta I_{s1} \left( \frac{T_{o_{\text{max}}}}{V_{s1} \cdot 0.25} \right) \]

\[ C_{o1} = 9.7 \, \mu\text{F} \]

- Maximum ESR value:

\[ E_{SR1} := \frac{V_{\text{rp1}} \cdot 0.75}{\Delta I_{s1}} \]

\[ E_{SR1} = 1.59 \, \text{ohm} \]

- Minimum output capacitance:

\[ C_{o2} := \Delta I_{s2} \left( \frac{T_{o_{\text{max}}}}{V_{s2} \cdot 0.25} \right) \]

\[ C_{o2} = 1.26 \times 10^4 \, \mu\text{F} \]

- Maximum ESR value:

\[ E_{SR2} := \frac{0.75 \cdot V_{\text{rp2}}}{\Delta I_{s2}} \]

\[ E_{SR2} = 1.23 \times 10^{-3} \, \text{ohm} \]

7) Input capacitor:

The input capacitor has to meet the maximum ripple current rating \( I_{p_{\text{rms}}} \) and the maximum input voltage ripple ESR value.

8) Switching Mosfet: Power Dissipation

The Mosfet is chosen based on maximum Stress voltage (section1), maximum peak input current
(section 3), total power losses, maximum allowed operating temperature, and driver capability of the LM3488.

- The drain to source Breakdown of the mosfet (Vdss) has to be greater than: $V_{dss_{\text{max}}} = 637.86\ \text{volt}$

- Continuous Drain current of the mosfet (Id) has to be greater than: $I_{p_{pk}} = 2.89\ \text{amp}$

- Maximum drive voltage:

  The voltage on the drive pin of the LM3488, Vdr is equal to the input voltage when input voltage is less than 7.2V, and Vdr is equal to 7.2V when the input voltage is greater than 7.2V

  $$V_{dr} := 7.2\ \text{volt}$$

  $$R_{dr_{on}} := 7\ \text{ohm}$$

- Total Mosfet's losses and maximum junction temperature:

  The goal in selecting a Mosfet is to minimize junction temperature rise by minimizing the power loss while being cost effective. Besides maximum voltage rating, and maximum current rating, the others three important parameters of a Mosfet are $R_{ds(on)}$, gate threshold voltage, and gate capacitance. The switching Mosfet has three types of losses, conduction loss and switching loss, and gate charge losses:

  - **Conduction losses** are equal to: $I^2R$ losses, therefore the total resistance between the source and drain during the on state, $R_{ds(on)}$ has to be as low as possible.

  - **Switching losses** are equal to: Switching-time*Vds*frequency. The switching time, rise time and fall time is a function of the gate to drain Miller-charge of the Mosfet, $Q_{gd}$, the internal resistance of the driver and the Threshold Voltage, $V_{gs(th)}$ the minimum gate voltage which enables the current through drain source of the Mosfet.

  - **Gate charge losses** are caused by charging up the gate capacitance and then dumping the charge to ground every cycle. The gate charge losses are equal to: frequency • $Q_{g_{(tot)}}$ • Vdr

    Unfortunately, the lowest on resistance devices tend to have higher gate capacitance. Because this loss is frequency dependent, in very high current supplies with very large FETs, with large gate capacitance, a more optimal design may result from reducing operating frequency. Switching losses are also effected by gate capacitance. If the gate driver has to charge a larger capacitance, then the time the Mosfet spends in the linear region increases and the losses increase. The faster the rise time, the lower the switching loss. Unfortunately this causes high frequency noise.

  $$n := 10^{-9}$$

<table>
<thead>
<tr>
<th>Mosfet:</th>
<th>$R_{ds_{on}} := 0.200\ \text{ohm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Total resistance between the source and drain during the on state)</td>
</tr>
<tr>
<td></td>
<td>$C_{oss} := 95\ \text{pF}$</td>
</tr>
<tr>
<td></td>
<td>(Output capacitance)</td>
</tr>
<tr>
<td></td>
<td>$Q_{g_{tot}} := 13\ \text{n-coul}$</td>
</tr>
<tr>
<td></td>
<td>(Total gate charge)</td>
</tr>
<tr>
<td></td>
<td>$Q_{gd_{miller}} := 6.1\ \text{n-coul}$</td>
</tr>
<tr>
<td></td>
<td>(Gate drain Miller charge)</td>
</tr>
<tr>
<td></td>
<td>$V_{gs_{th}} := 2\ \text{volt}$</td>
</tr>
<tr>
<td></td>
<td>(Threshold voltage)</td>
</tr>
</tbody>
</table>

- **Conduction losses: Pcond**

  $$P_{\text{cond}} := R_{ds_{on}} \cdot I_{p_{pk}}^2 \cdot D_{\text{max}}$$

  $$P_{\text{cond}} = 0.36\ \text{watt}$$

- **Switching losses: Psw(max)**

  **Turn On time:**

  $$t_{\text{sw}} := \frac{Q_{gd_{miller}}}{V_{dr} - V_{gs_{th}}} \cdot R_{dr_{on}}$$

  $$t_{\text{sw}} = 8.21 \times 10^{-9}\ \text{s}$$

  $$P_{sw_{\text{max}}} := \left( t_{\text{sw}} V_{ds_{\text{max}}} I_{p_{pk}} \cdot f_{\text{sw}} \right) + \frac{C_{oss} \cdot V_{ds_{\text{max}}}^2 f_{\text{sw}}}{2}$$

  $$P_{sw_{\text{max}}} = 3.45\ \text{watt}$$
- Gate charge losses: $P_{\text{gate}}$

Average current required to drive the gate capacitor of the Mosfet:

\[
I_{\text{gate}}_{\text{avg}} := \text{fsw} \cdot Q_{\text{g}}_{\text{tot}}
\]

\[
I_{\text{gate}}_{\text{avg}} = 1.3 \times 10^{-3} \text{ amp}
\]

\[
P_{\text{gate}} := I_{\text{gate}}_{\text{avg}} \cdot V_{\text{dr}}
\]

\[
P_{\text{gate}} = 9.36 \times 10^{-3} \text{ watt}
\]

- Total losses: $P_{\text{tot(max)}}$

\[
P_{\text{mosfet tot}} := P_{\text{cond}} + P_{\text{sw max}} + P_{\text{gate}}
\]

\[
P_{\text{mosfet tot}} = 3.82 \text{ watt}
\]

- Maximum junction temperature and heat sink requirement:

Maximum junction temperature desired: \( T_{j_{\text{max}}} := 140 \) Celsius

Maximum ambient temperature: \( T_{a_{\text{max}}} := 70 \) Celsius

- Thermal resistance junction to ambient temperature:

\[
\theta_{ja} := \frac{T_{j_{\text{max}}} - T_{a_{\text{max}}}}{P_{\text{mosfet tot}}}
\]

\[
\theta_{ja} = 18.32 \text{ } \frac{\text{watt}}{\text{Celsius}}
\]

If the thermal resistance calculated is lower than that one specified on the Mosfet’s data sheet a heat sink or higher copper area is needed.

For Example for a T0-263 (D2pak) package the $T_{ja}$ of the Mosfet versus copper plane area is:

10) Current limit:

The LM3488 uses a current mode control scheme. The main advantages of current mode control are inherent cycle-by-cycle current limit for the switch, and simple control loop characteristics.

Since the LM3488 has a maximum duty cycle of 100%, the current limit should be designed to have current limit just above the maximum primary peak current plus 20-30%.

\[
R_{\text{sense}} := \frac{160 \cdot \text{mV}}{I_{p_{\text{pk}}} \cdot 1.2}
\]

\[
R_{\text{sense}} = 0.05 \text{ } \Omega
\]

11) Transformer Design:

The inductor-transformer should be designed to minimize the leakage inductance, AC winding losses, and core losses.

In continuous mode of operation, the total amper-turns never goes to zero, therefore the transformer will have lower core losses, and high AC winding losses.

Unipolar pulses cause DC current to flow through the core winding, moving the flux in the core from $B_r$ towards saturation. When pulses goes to zero, the flux travels back to $B_r$. The transformer in flyback power supply acts as an energy storage device, therefore to do not saturate is used a air-gapped ferrite core or Molypermalloy Powdered cores with distributed air-gap.
The power handling capacity of the transformer core can be determined by its WaAc product area, where Wa is the available core window area, and Ac is the effective core cross-sectional area. The WaAc power output relationship is obtained with the Faraday's law:

\[ E = 4BAcNf \times 10^{-8} \]

Where:
- \( E \) = applied voltage
- \( J \) = current density \( \text{amp/cm}^2 \)
- \( B \) = flux density in gauss
- \( K \) = winding factor
- \( I \) = current (rms)
- \( N \) = number of turns
- \( Po \) = output power
- \( f \) = frequency
- \( Wa \) = window area in \( \text{cm}^2 \)

- Select maximum current density of the windings:

\[ J = \begin{cases} 280 - 390 \text{ amp/cm}^2, & \text{or} \\ 400 - 500 \text{ circular-mils/amp} \end{cases} \]

- Winding factor:

\[ K = 0.2 \] (0.2-0.3 for flyback continuous mode)

- Select core material and maximum flux density:

It is assume that at high switching frequency (fsw>>25KHz) the limitation factor is the core losses, and temperature rise of the transformer. The type of ferrite material chosen will influence the core losses at the given operating conditions:
- F material has its lowerst losses at room temperature to 40°C.
- P material has lowerst losses at 70°C-80°C.
- R material has lowerst losses at 100°C-110°C.
- K material has lowerst losses at 40°C-60°C at elevated frequencies.

At high switching frequency it is necessary to adjust the flux density in order to limit core temperature rise: limiting core losses density to 100mW/cm³ would keep the temperature rise at approximately 40°C.

Use the following formula to select the most appropriate maximum flux density:

- Maximum core losses density:

\[ P_{\text{cored}} = 250 \text{ mW/cm}^3 \]

for **P material**:

- for frequency \( f < 100\text{kHz} \):
  - \( a = 0.158 \)
  - \( b = 1.36 \)
  - \( c = 2.86 \)

- for frequency \( 100\text{kHz} < f < 500\text{kHz} \):
  - \( a = 7.36 \times 10^{-7} \)
  - \( b = 3.47 \)
  - \( c = 2.54 \)

- for frequency \( f > 500\text{kHz} \):
  - \( a = 1.77 \times 10^{-9} \)
  - \( b = 4.13 \)
  - \( c = 2.98 \)

for **K material**:

- for frequency \( f < 500\text{kHz} \):
  - \( a = 0.0530 \)
  - \( b = 1.60 \)
  - \( c = 3.15 \)

- for frequency \( 500\text{kHz} < f < 1 \text{ MHz} \):
  - \( a = 0.00113 \)
  - \( b = 2.19 \)
  - \( c = 3.10 \)

- for frequency \( f > 1 \text{ MHz} \):
  - \( a = 1.77 \times 10^{-9} \)
  - \( b = 4.13 \)
  - \( c = 2.98 \)
\[ B := \left[ \frac{P_{\text{cored}}}{a_1 \frac{f_{\text{sw}}}{\text{kHz}}} \right]^{b_1} \cdot 10^3 \text{ gauss} \]

\[ B = 1.55 \times 10^3 \text{ gauss} \]

\[ \Delta B := B \cdot 2 \]

\[ \Delta B = 3.1 \times 10^3 \text{ gauss} \]

**Topology constant:**

\[ K_t := \frac{0.00025}{1.97} \cdot 10^3 \]

\[ WaAc := \frac{P_{o_{\text{max}}}}{K_t \cdot \Delta B \cdot f_{\text{sw}} \cdot J} \]

\[ WaAc = 0.71 \text{ cm}^4 \]

**Select a core with Area Product larger than :***

\[ WaAc = 0.71 \text{ cm}^4 \]

**Core selected:**

- Manufacture: EPCOS
- Material: N87
- Shape: ETD core
- Part number: ETD34
- Core Area: \( A_e \)
- Bobbin area: \( W_a \)
- Core volume: \( V_e \)
- Window length: \( l_w \)
- Area product: Used

\[ A_e \cdot W_a = 1.18 \text{ cm}^4 \]

**Inductance per 1000 turns without airgap :**

\[ l_p \text{ } l_{pk} \]

The number of turns has to be rounded to the higher or lower integer value: \( N_p := 82 \)

\[ N_p A_e \cdot \Delta B \]

\[ l_p \text{ } l_{pk} = 853.7 \mu H \]

**Primary inductance: Primary turns**

\[ N_{p_c} := \frac{L_p \cdot l_{pk}}{\Delta B \cdot A_e} \]

\[ N_{p_c} = 81.55 \]

**Secondary inductance: Secondary turns**

\[ N_{s1_c} := \left( \frac{N_p}{N_{s1}} \right) \]

\[ N_{s1_c} = 94.16 \]

\[ N_{s1} := 94 \]
\[ Ns_2c := \left( \frac{Np}{Nps2} \right) \quad Ns_2c = 0.61 \quad Ns_2 := 0 \]

**Air-gap length**

The air-gap length is proportional to the effective gap section area (\(Ag\)). 
\(Ag\) is equal to the core section times the finging coefficient, that take in consideration the finging flux in the air-gap. Since \(Ag\) depends on the air-gap length itself, the air-gap length (\(L_g\)) can be calculated with few iterations of a loop cycle.

\[
L_g := \frac{\mu_0}{4 \pi} \cdot 10^{-7} \text{ henry/m} \\

\text{for } i \in 0..4 \\
\text{lgap} := \frac{\mu_0}{\text{cm}} \cdot \text{henry} \cdot Np^2 \cdot \left( \frac{Ag}{L_p} \text{henry} \right) \\
Ag := \frac{\text{Ae}}{\text{cm}^2} \left( 1 + \frac{\text{lgap}}{\sqrt{\frac{\text{Ae}}{\text{cm}^2}}} \log \left( \frac{2 \cdot \text{lw}}{\text{cm} \cdot \text{lgap}} \right) \right) \\
\text{(Air-gap length)} \\
L_g = 1.14 \cdot \text{mm} \\
L_g = 0.04 \cdot \text{in} \\

- Primary and secondary wire size:

Maximum current density: \( J = 390 \text{ amp/cm}^2 \)

Primary rms current: \( I_{p_{rms}} = 1.88 \text{ amp} \)

**Primary:**

by wire area:
\[ W_{p_{cu}} := \frac{I_{p_{rms}}}{J} \quad W_{p_{cu}} = 4.82 \cdot 10^{-3} \text{ cm}^2 \]

or by wire size:
\[ \text{AWG}_{p} := -4.2 \cdot \ln \left( \frac{W_{p_{cu}}}{\text{cm}^2} \right) \quad \text{AWG}_{p} = 22.4 \quad (\text{Approximated AWG wire size, for more precision refer to wire size table}) \]

**Primary Wire selected:**

Wire size

Bare area (copper plus insulation)

Copper area:

Diameter

Number of strands:

\[ \text{AWG}_{L_p} := 25 \]

\[ \text{Wa}_{L_p} := 2.10^{-3} \text{ cm}^2 \]

\[ \text{Wcu}_{L_p} := 2.514 \cdot 10^{-3} \text{ cm}^2 \]

\[ \text{Dcu}_{L_p} := 0.0505 \text{ cm} \]

\[ \text{Nst}_{L_p} := 2 \]
- **Number of primary turns per layer**: \( N_{\text{tl,}\ LP} := \text{floor} \left( \frac{lw}{D_{\text{cu,}\ LP}} \right) \)
  \( N_{\text{tl,}\ LP} = 41 \)

- **Number of primary layers**: \( N_{\text{ly,}\ LP} := \text{ceil} \left( \frac{N_{\text{p}} \cdot N_{\text{st,}\ LP}}{N_{\text{tl,}\ LP}} \right) \)
  \( N_{\text{ly,}\ LP} = 4 \)

**Secondary: Master**

by wire area: \( W_{s1\ cu} := \frac{I_{s1\ rms}}{J} \)
\( W_{s1\ cu} = 3.68 \cdot 10^{-3} \cdot \text{cm}^2 \)

or by wire size: \( \text{AWGs1} := -4.2 \cdot \ln \left( \frac{W_{s1\ cu}}{\text{cm}^2} \right) \)
\( \text{AWGs1} = 23.54 \)

Secondary Wire selected:
Wire size
Bare area (copper plus insulation)
Copper area:
Diameter
Number of strands:
\( \text{AWG}_{\text{Ls1}} := 25 \)
\( W_{a_{\text{Ls1}}} := 2 \cdot 10^{-3} \cdot \text{cm}^2 \)
\( W_{c_{\text{uLs1}}} := 2.514 \cdot 10^{-3} \cdot \text{cm}^2 \)
\( D_{\text{cuLs1}} := 0.0505 \cdot \text{cm} \)
\( \text{Nst}_{\text{Ls1}} := 2 \)

- **Number of secondary turns per layer**: \( N_{\text{tl,}\ LS1} := \text{floor} \left( \frac{lw}{D_{\text{cu,}\ LS1}} \right) \)
  \( N_{\text{tl,}\ LS1} = 41 \)

- **Number of secondary layers**: \( N_{\text{ly,}\ LS1} := \text{ceil} \left( \frac{N_{\text{s1}} \cdot N_{\text{st,}\ LS1}}{N_{\text{tl,}\ LS1}} \right) \)
  \( N_{\text{ly,}\ LS1} = 5 \)

by wire area: \( W_{s2\ cu} := \frac{I_{s2\ rms}}{J} \)
\( W_{s2\ cu} = 37.89 \cdot 10^{-3} \cdot \text{cm}^2 \)

or by wire size: \( \text{AWGs2} := -4.2 \cdot \ln \left( \frac{W_{s2\ cu}}{\text{cm}^2} \right) \)
\( \text{AWGs2} = 13.75 \)

**Secondary: Slave**

Secondary Wire selected:
Wire size
Bare area (copper plus insulation)
Copper area:
Diameter
Number of strands:
\( \text{AWG}_{\text{Ls2}} := 26 \)
\( W_{a_{\text{Ls2}}} := 1.63 \cdot 10^{-3} \cdot \text{cm}^2 \)
\( W_{c_{\text{uLs2}}} := 1.28 \cdot 10^{-3} \cdot \text{cm}^2 \)
\( D_{\text{cuLs2}} := 0.0452 \cdot \text{cm} \)
\( \text{Nst}_{\text{Ls2}} := 1 \)

- **Number of secondary turns per layer**: \( N_{\text{tl,}\ LS2} := \text{floor} \left( \frac{lw}{D_{\text{cu,}\ LS2}} \right) \)
  \( N_{\text{tl,}\ LS2} = 46 \)
- Number of secondary layers: \[ N_{ly_{Ls2}} := \text{ceil} \left( \frac{N_{s2} \cdot N_{st_{Ls2}}}{N_{tl_{Ls2}}} \right) \]

\[ N_{ly_{Ls2}} = 0 \]

- Copper area: \[ W_{cu_{tot}} := (D_{cu_{Lp}} \cdot N_{ly_{Lp}} + D_{cu_{Ls1}} \cdot N_{ly_{Ls1}} + D_{cu_{Ls2}} \cdot N_{ly_{Ls2}}) \cdot 1.15 \cdot lw \]

\[ W_{cu_{tot}} = 1.09 \cdot \text{cm}^2 \]

- Window utilization:

\[ W_u := \frac{W_{cu_{tot}}}{W_a} \]

\[ W_u = 89.54\% \]

Important: if Window utilisation is greater than 90%, (Copper area >> than bobbin area) a core with larger window area, or smaller wire sizes must be selected.

- Core losses:

\[ P_{core} := V_e \left[ \frac{B}{10^3 \text{ gauss}} \right]^{c_1} \cdot a_1 \left( \frac{f_{sw}}{\text{kHz}} \right)^{b_1} \cdot 10^{-3} \text{ watt cm}^{-3} \]

\[ P_{core} = 1.91 \text{ watt} \]

- Winding copper losses:

There are two effects, which can cause the winding losses to be significantly greater than \( I^2 \cdot R_{cu} \): skin and proximity effects.

Skin effect causes current in a wire to flow only in a thin skin of the wire.

Skin depth: distance below the surface where the current density has fallen to 1/e of its value at the surface: \( S_d \)

\[ S_d := \frac{6.61}{\sqrt{\frac{f_{sw}}{\text{Hz}}}} \cdot \text{cm} \]

\[ S_d = 0.02 \cdot \text{cm} \]

\[ L_t = 6.05 \cdot \text{cm} \]

\[ N_{ly_{Lp}} = 4 \]

To minimize the AC copper losses in a transformer, if the wire diameter is greater than two times the skin depth, a multi-strands winding or litz wires should be considered.

If \( D_{cu_{Lp}} = 0.05 \cdot \text{cm} \) is greater than \( S_d \cdot 2 = 0.04 \cdot \text{cm} \)

Primary winding length:

\[ L_{cu_{Lp}} := \begin{cases} \frac{L_1}{L} \leftarrow L_t \\ \frac{L}{L} \leftarrow 0 \cdot \text{cm} \\ \text{for } i \in 1 .. (N_{ly_{Lp}} - 1) \\ \frac{L}{L} \leftarrow L_1 + N_{tl_{Lp}} \\ \frac{L_1}{L_1} \leftarrow L_1 + 4 \cdot D_{cu_{Lp}} \\ \left[ L + L_1 \cdot \left( N_{p} - (N_{ly_{Lp}} - 1) \cdot N_{tl_{Lp}} \right) \right] \end{cases} \]

\[ N_p = 82 \]
Copper resistivity: (20°C) \( \rho_{20} := 1.724 \times 10^{-6} \text{ Ω·cm} \)  
- Maximum temperature of the winding: \( T_{\text{max}_\text{Cu}} := 80 \)

\[
\rho := \rho_{20} \left[ 1 + 0.0042 \left( T_{\text{max}_\text{Cu}} - 20 \right) \right]
\]

\[
R_{\text{dc}_{LP}} := \rho \frac{L_{\text{cu}_{LP}}}{W_{\text{cu}_{LP}} \cdot N_{\text{st}_{LP}}}
\]

\[
R_{\text{ac}_{LP}} := \frac{R_{\text{dc}_{LP}} \left( \frac{D_{\text{cu}_{LP}}}{2 \cdot S_d} \right)^2}{\left( \frac{D_{\text{cu}_{LP}}}{2 \cdot S_d} \right)^2 - \left( \frac{D_{\text{cu}_{LP}}}{2 \cdot S_d} - 1 \right)^2}
\]

\[
P_{\text{cu}_{LP}} := R_{\text{dc}_{LP}} \cdot I_{\text{p}_{ac}}^2 + R_{\text{ac}_{LP}} \cdot I_{\text{p}_{ac}}^2
\]

Secondary winding length:

\[
L_{\text{cu}_{LS1}} := \begin{cases} 
L1 & \text{← } L_{\text{df}_{LP}} \\
L & \text{← } 0 \text{ cm} \\
\text{for } i \in 1.. \left( N_{\text{ly}_{LS1}} - 1 \right) \\
L & \text{← } L + L1 \cdot N_{\text{ly}_{LS1}} \\
L1 & \text{← } L1 + 4 \cdot D_{\text{cu}_{LS1}} \\
L & \text{← } 0 \text{ if } N_{\text{ly}_{LS1}} \rightarrow 1 \\
\left[ L + L1 \cdot \left( N_{\text{nl}_{LS1}} - \left( N_{\text{ly}_{LS1}} - 1 \right) \cdot N_{\text{nl}_{LS1}} \right) \right] 
\end{cases}
\]

\[
L_{\text{cu}_{LS1}} = 701.62 \text{ cm}
\]

\[
R_{\text{dc}_{LS1}} := \rho \frac{L_{\text{cu}_{LS1}}}{W_{\text{cu}_{LS1}} \cdot N_{\text{st}_{LS1}}}
\]

\[
R_{\text{ac}_{LS1}} := \frac{R_{\text{dc}_{LS1}} \left( \frac{D_{\text{cu}_{LS1}}}{2 \cdot S_d} \right)^2}{\left( \frac{D_{\text{cu}_{LS1}}}{2 \cdot S_d} \right)^2 - \left( \frac{D_{\text{cu}_{LS1}}}{2 \cdot S_d} - 1 \right)^2}
\]

\[
P_{\text{cu}_{LS1}} := R_{\text{dc}_{LS1}} \cdot I_{\text{p}_{ac}}^2 + R_{\text{ac}_{LS1}} \cdot I_{\text{p}_{ac}}^2
\]
\begin{align*}
L_{cu_{ls2}} &:= L_1 \leftrightarrow L_{df_{ls1}} \\
L &\leftarrow 0 \cdot \text{cm} \\
\text{for } & \quad i \in 1 \ldots (N_{ly_{ls2}} - 1) \\
L &\leftarrow L + L_1 \cdot N_{ly_{ls2}} \\
L_1 &\leftarrow L_1 + 4 \cdot D_{cu_{ls2}} \\
L &\leftarrow 0 \quad \text{if } \quad N_{ly_{ls2}} \leftarrow 1 \\
[L + L_1 \cdot N_{ls2} - (N_{ly_{ls2}} - 1) \cdot N_{tl_{ls2}}]
\end{align*}

\[ L_{cu_{ls2}} = 0 \cdot \text{cm} \]

\begin{align*}
R_{dc_{ls2}} &:= \frac{L_{cu_{ls2}}}{W_{cu_{ls2}} \cdot N_{st_{ls2}}} \\
R_{ac_{ls2}} &:= \frac{D_{cu_{ls2}}}{2 \cdot S_d} \cdot \left( \frac{D_{cu_{ls2}}}{2 \cdot S_d} - 1 \right)^2 \\
P_{cu_{ls2}} &:= R_{dc_{ls2}} \cdot I_{o2_{\text{max}}}^2 + R_{ac_{ls2}} \cdot I_{s2_{ac}}^2 \\
P_{cu_{\text{tot}}} &:= P_{cu_{lp}} + P_{cu_{ls1}} + P_{cu_{ls2}} \\
-\text{Total transformer's losses:} \\
P_{\text{trans}_{\text{tot}}} &:= P_{cu_{\text{tot}}} + P_{\text{core}} \\
-\text{Transformer's efficiency:} \\
\eta_{\text{tra}} &:= \frac{P_{o_{\text{max}}}}{P_{o_{\text{max}}} + P_{\text{trans}_{\text{tot}}}} \\
\eta_{\text{tra}} &\approx 97.05 \% \\
12) \text{Total Power Supply Efficiency:} \\
P_{\text{out}} &:= V_{o1} \cdot I_{o1_{\text{max}}} + V_{o2} \cdot I_{o2_{\text{max}}} \\
\eta_{\text{tot}} &:= \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{trans}_{\text{tot}}} + P_{\text{diode}_{\text{tot}}} + P_{\text{mosfet}_{\text{tot}}}} \\
\eta_{\text{tot}} &\approx 89.52 \% \\
13) \text{Select the proper switching frequency:}
\end{align*}

The operating frequency of the power supply should be selected to obtain the best balance between switching losses, total transformer losses, size and cost of magnetic components and output capacitors. High switching frequency reduces the output capacitor value and the inductance of the primary and secondary windings, and therefore the total size of the transformer.

In the same manner, higher switching frequency increases the transformer losses and the switching losses of the switching transistor. High losses reduce the overall efficiency of the power supply, and increase the
size of the heat-sink required to dissipate the heat.

Notes:

Wire table:

<table>
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<tr>
<th>AWG Wire Size</th>
<th>Bar Area cm&lt;sup&gt;2&lt;/sup&gt; 10&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>Area cm&lt;sup&gt;2&lt;/sup&gt; 10&lt;sup&gt;-3&lt;/sup&gt;</th>
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References:

1. Rudolf P. Severns, Gordon E. Bloom "Modern DC to DC switchmode power converter circuits".
2. Magnetics application notes.
3. Colonel Wm. T. McLyman "Transformer and Inductor Design Handbook"
4. Pressman "Switching Power Supply Design"
5. R. Martinelli, C. Hymowitz, Intusoft "Designing a 12.5W 50kHz Flyback Transformer"