TinySwitch™ Flyback Design Methodology

Application Note AN-23

Introduction

This document describes a simple Design Methodology for flyback power supply design using the *TinySwitch* family of integrated off-line switchers. The objective of this Design Methodology is to provide power supply engineers a handy tool that not only eases the design task but also delivers design optimization in cost and efficiency for most applications.

Basic Circuit Configuration

Because of the high level integration of *TinySwitch*, flyback power supply design is greatly simplified. As a result, the basic circuit configuration of *TinySwitch* flyback power supplies remains unchanged from application to application. Application specific issues outside this basic configuration such as constant current, constant power outputs, etc. are beyond the scope of this document.

Figure 1 shows the basic circuit configuration in a typical *TinySwitch* flyback design using TNY253.

Design Flow

Figures 2A, B and C present a design flow chart showing the complete design procedure in 22 steps. The logic behind this Design Methodology can be summarized as follows:

1. Calculate minimum reflected voltage, V_{OR}, allowed by a given output diode.
2. Design for discontinuous mode operation using this calculated V_{OR}. If necessary, increase V_{OR}.
3. At V_{OR} = 150 V, select bigger *TinySwitch* to stay in discontinuous mode or go to continuous mode design.
4. Design transformer using EE16 core.
5. Select feedback circuit and other components to complete the design.

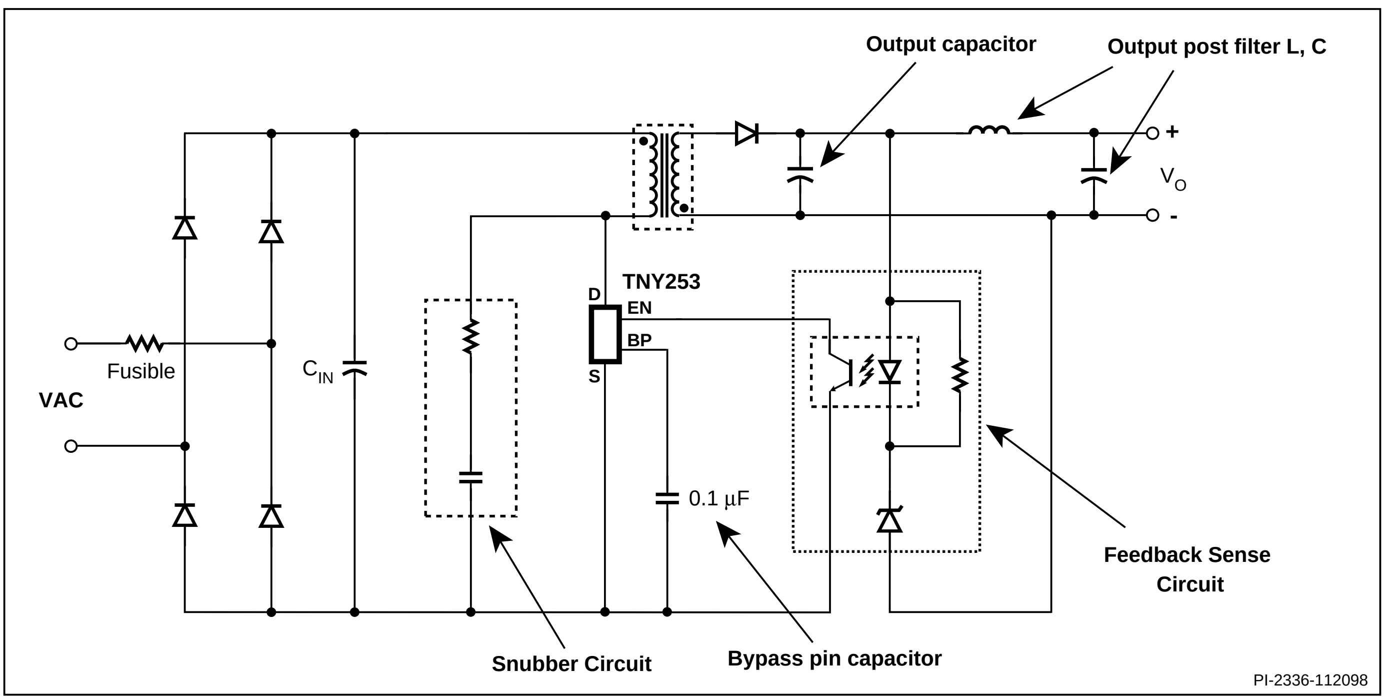

Figure 1. Typical TinySwitch Flyback Power Supply.

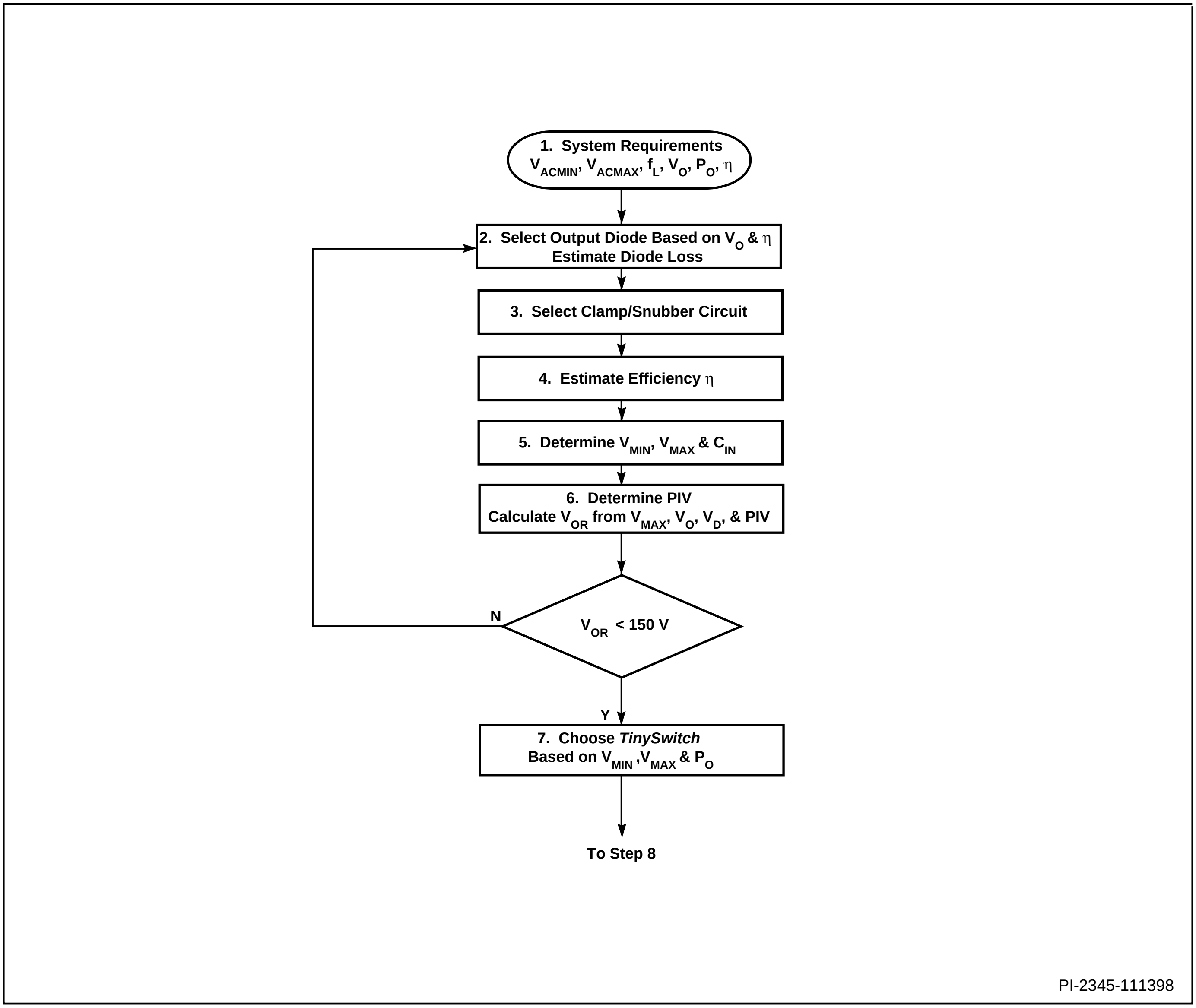

Figure 2A. TinySwitch Flyback Design Flowchart Steps 1 to 7.

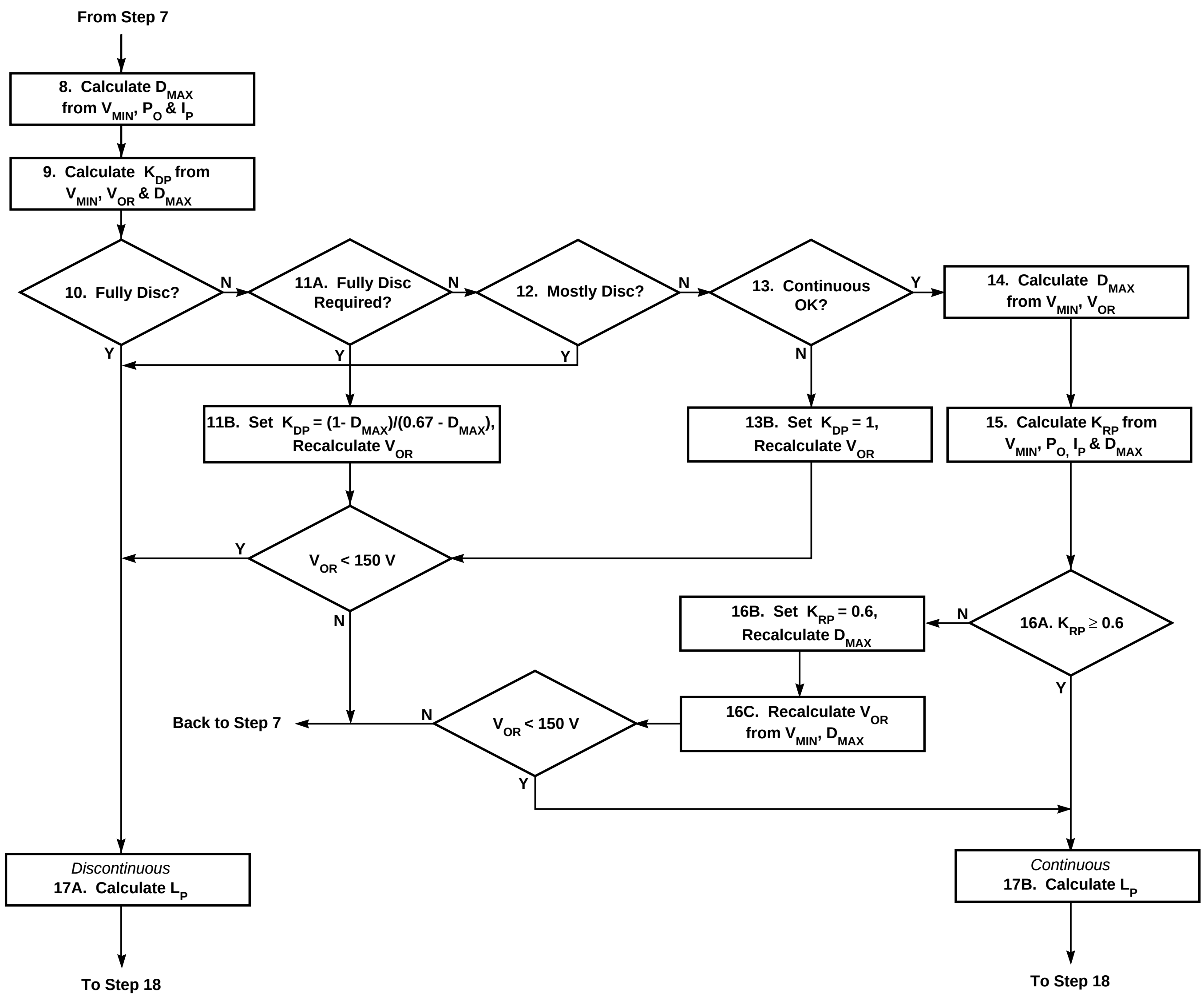

Figure 2B. TinySwitch Flyback Design Flowchart Steps 8 to 17A, B.

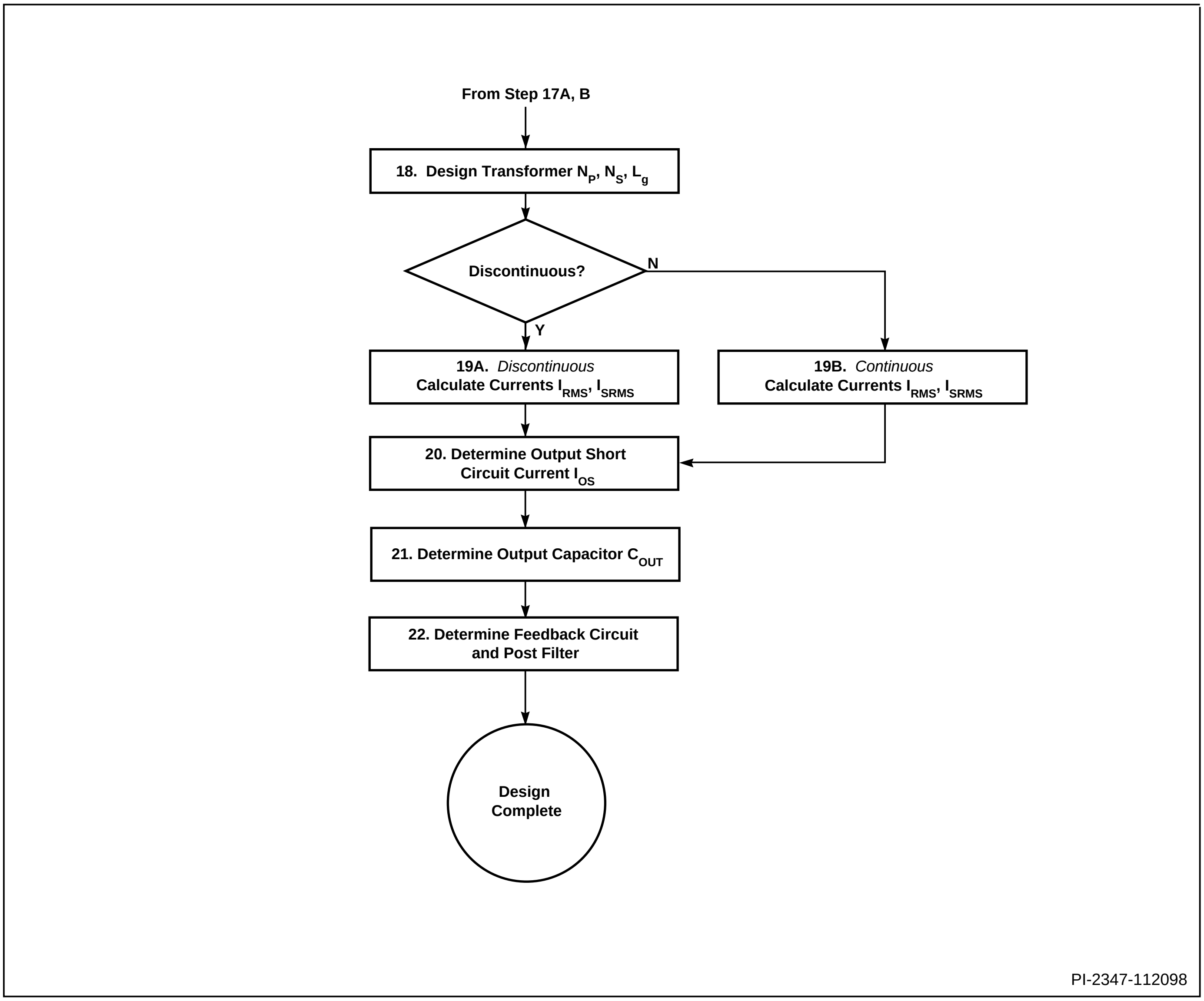

Figure 2C. TinySwitch Flyback Design Flowchart Steps 18-22.

Step by Step Design Procedure

Symbols and parameters used in this design procedure are defined in Application Note "*TOPSwitch* Flyback Design Methodology" (AN-16).

Step 1.
Determine system requirements: V_{ACMIN}, V_{ACMAX}, f_L, V_O, P_O, η

- Determine input voltage range from Table 1.

Input (VAC)	V_{ACMIN} (VAC)	V_{ACMAX} (VAC)
100/115	85	132
230	195	265
Universal	85	265

Table 1. Input Voltage Range.

Step 2.
Select output diode. Estimate associated efficiency loss.

- The output diode can be selected based on expected power supply efficiency and cost (see Table 2).
  - Use a Schottky diode for highest efficiency for output voltages up to 7.5 V.
  - For output voltages beyond 7.5 V use an Ultra Fast PN-diode.
  - If efficiency is not a concern (or cost is paramount), use a Fast PN-diode.
  - The Schottky and Ultrafast may be used with continuous mode of operation. The Fast PN-diode should be used only with discontinuous mode of operation.
  - Choose output diode type. Table 2 shows approximate forward voltage (V_D) for types of output diode discussed above.

- Output diode efficiency loss is the power supply efficiency reduction (in percentage) caused by the diode.

Diode Type	V_D (V)	Efficiency Loss
Schottky	0.5	$(0.5/V_O) \times 100\%$
Ultrafast-PN	1.0	$(1.0/V_O) \times 100\%$
Fast-PN	1.0	$(1.0/V_O) \times 100\%$

Table 2. Diode forward voltage (V_D) and efficiency loss.

- The estimated efficiency loss due to the output diode is also shown in Table 2.
- Table 3 shows some commonly used output diodes. V_R is the diode reverse voltage rating. I_D is the diode DC current rating.
- The final diode current rating is to be determined in Step 20 to accommodate continuous short circuit current I_{OS}.

Output Diode		V_R (V)	I_D (A)	Manufacturer
Schottky	1N5819	40	1.0	Motorola
	1N5822	40	3.0	Motorola
	MBR745	45	7.5	Motorola
	MBR1045	45	10.0	Motorola
	MBR1645	45	16.0	Motorola
UFR	UF4002	100	1.0	GI
	MUR110	100	1.0	Motorola
	MUR120	200	1.0	Motorola
	UF4003	200	1.0	GI
	BYV27-200	200	2.0	Philips, GI
	UF5401	100	3.0	GI
	UF5402	200	3.0	GI
	MUR410	100	4.0	Motorola
	MUR420	200	4.0	Motorola
	MUR810	100	8.0	Motorola
	MUR820	200	8.0	Motorola
	BYW29-200	200	8.0	Philips, GI
	BYV32-200	200	20.0	Philips

Table 3. Output diodes.

Step 3.
Select clamp/snubber circuit and determine associated efficiency loss.

- Clamp/snubber circuit is required at DRAIN to keep DRAIN voltage below rated BV:

  - A snubber alone may be used at low power (< 3 W with Universal input) and will provide lower video noise and superior EMI performance.

  - An RCD clamp may be used for power levels < 3 W for higher efficiency and is required at power levels > 3 W with Universal input.

- Table 4 shows the approximate efficiency loss due to clamp/snubber circuits.

Clamp/Snubber	P_O	Efficiency Loss
RC Snubber	0 to 3 W	20%
RCD clamp	> 3 W	15%

Table 4. Clamp/Snubber efficiency loss.

Step 4.
Estimate power supply efficiency η.

- Total efficiency loss is the sum of the output diode efficiency loss (from Step 2) and the clamp/snubber efficiency loss (from Step 3).

- Calculate overall power supply efficiency as: η = 100% - total efficiency loss.

Step 5.
Determine maximum and minimum DC input voltages V_{MAX}, V_{MIN} and input storage capacitance C_{IN}. (see AN-16 for more detail)

- Calculate the maximum V_{MAX} as:

$$V_{MAX} = \sqrt{2} \times V_{ACMAX}$$

- Choose input storage capacitor, C_{IN} per Table 5.

Input Voltage	C_{IN} (µF/Watt)	V_{MIN} (V)
100/115	2-3	≥ 90
230	1	≥ 240
Universal	2-3	≥ 90

Table 5. C_{IN} Range.

- Set bridge rectifier conduction time t_c = 3 ms.
- Derive minimum DC input voltage, V_{MIN}

$$V_{MIN} = \sqrt{\left(2 \times V_{ACMIN}{}^{2}\right) - \frac{2 \times P_O \times \left(\frac{1}{2 \times f_L} - t_C\right)}{\eta \times C_{IN}}}$$

where C_{IN} : input capacitance
f_L : line frequency
t_c : diode conduction time

Step 6.
Determine output diode peak inverse voltage PIV. Calculate reflected output voltage V_{OR} based on V_{MAX}, V_O, V_D and PIV.

- Look up output diode reverse voltage V_R from diode data sheet or Table 3 in Step 2.
- Calculate maximum peak inverse voltage PIV. The maximum recommended PIV is 80% of the reverse voltage rating V_R.

$$PIV = 0.8 \times V_R$$

- Calculate reflected output voltage V_{OR}:

$$V_{OR} = \frac{V_{MAX} \times (V_O + V_D)}{PIV - V_O}$$

- If V_{OR} > 150 V, go back to Step 2 and choose a different diode for higher V_R.
- Refer to Table 6 for approximate V_R range for different types of diodes.

Diode Type	V_R (V)
Schottky	40-45
UltraFast-PN	100-200
Fast-PN	> 200

Table 6. Diode reverse voltage range.

Step 7.
Choose *TinySwitch* based on input voltage range and output power P_O.

- Select appropriate *TinySwitch* according to Table 7 based on output power P_O and input voltage range (from Step 1).

	Output Power Capability (W)		Recommended Power Range for Lowest Cost** (W)	
Device	P_O for Single Voltage*	P_O for Universal Voltage	P_O for Single Voltage*	P_O for Universal Voltage
TNY253	5.0	2.5	0-2.5	0-1.5
TNY254	8.0	5.0	2.0-5.0	1.0-4.0
TNY255	10	7.5	6.0-10	3.5-6.5

Table 7. TinySwitch *output power (P_O) capability*

* Single Voltage 100/115 VAC with voltage doubler, or Single Voltage 230 VAC without doubler
** Based on EE16 core transformer

- For Universal input voltage and an output power range of 1W to 1.5 W, TNY254 is usually a better choice than TNY253 except for applications requiring low video noise.
- For Universal input voltage and an output power range of 3.5W to 4 W, TNY255 usually results in smaller transformer size and higher efficiency than TNY254.

Step 8.
Determine primary peak current I_P. Calculate maximum duty cycle D_{MAX} for discontinuous mode of operation based on V_{MIN}, P_O and I_P.

- Primary peak current is 90% of minimum I_{LIMIT} from the data sheet of the selected *TinySwitch*. 0.9 is the over temperature derating factor for I_{LIMIT}:

$$I_P = 0.9 \times \text{minimum } I_{LIMIT}$$

- Calculate maximum duty cycle D_{MAX} for discontinuous mode of operation as:

$$D_{MAX} = \frac{2 \times P_O}{\eta \times V_{MIN} \times I_P}$$

Step 9.
Calculate K_{DP} from V_{MIN}, V_{OR} and D_{MAX}.

- KDP is the ratio between the off-time of the switch and the reset time of the core:

$$K_{DP} = \frac{V_{OR} \times (1 - D_{MAX})}{V_{MIN} \times D_{MAX}}$$

Step 10, 11A, 11B, 12, 13A, 13B.
Check K_{DP} to ensure discontinuous mode of operation. Raise V_{OR} if necessary.

The mode of operation can vary depending on power supply requirements. However, discontinuous mode of operation is always recommended wherever it is possible.

- With discontinuous mode of operation, generally, the output filter is smaller, output rectifier is cheaper with PN junction diode, EMI and video noise are lower.
- Fully discontinuous mode of operation (discontinuous under all conditions) may be necessary in some applications to meet specific requirements such as very low video noise, very low output ripple voltage. Use of RC snubber, and/or PN junction diode as output rectifier also demand fully discontinuous mode of operation. This can be accomplished by raising V_{OR} higher if necessary until $K_{DP} \geq (1 - D_{MAX})/(0.67 - D_{MAX})$. To keep the worst case DRAIN voltage below the recommended level of 650 V, V_{OR} should be kept below 150V.
- Mostly discontinuous mode of operation ($K_{DP} \geq 1$) refers to a design operating in discontinuous mode under most situations, but do have the possibility of operating in continuous mode occasionally.
- Continuous mode operation ($K_{DP} < 1$) provides higher output power. In this mode a Schottky output diode should be used to prevent long diode reverse recovery times that could exceed leading edge blanking period (t_{LEB}).

Step 10.
Check for fully discontinuous operation.

- $K_{DP} \geq (1 - D_{MAX})/(0.67 - D_{MAX})$: Fully discontinuous. Go to Step 17A.
- $K_{DP} < (1 - D_{MAX})/(0.67 - D_{MAX})$: Go to Step 11.
- 0.67 is the reciprocal of the percentage of duty cycle relaxation caused by various parameters such as the tolerance in *TinySwitch* current limit and frequency.

Step 11A, B.
Determine if fully discontinuous is necessary.

- If yes, set $K_{DP} = (1 - D_{MAX})/(0.67 - D_{MAX})$. Recalculate V_{OR} as

$$V_{OR} = \frac{K_{DP} \times V_{MIN} \times D_{MAX}}{1 - D_{MAX}}$$

  - If $V_{OR} < 150$ V, go to Step 17A.
  - If $V_{OR} > 150$ V, go back to Step 7 and select higher current *TinySwitch.*

- If not, go to Step 12.

Step 12.
Check for mostly discontinuous.

- $K_{DP} \geq 1$. Operation is mostly discontinuous. Go to Step 17A.
- $K_{DP} < 1$. Go to Step 13.

Step 13A, B.
Determine if continuous is acceptable for the application.

- If yes, go to Step 14.
- If not, set $K_{DP} = 1$. Recalculate V_{OR} as:

$$V_{OR} = \frac{K_{DP} \times V_{MIN} \times D_{MAX}}{1 - D_{MAX}}$$

  - If $V_{OR} < 150$ V, go to Step 17A.
  - If $V_{OR} > 150$ V, go back to Step 7 and select higher current *TinySwitch.*

Step 14.
Recalculate D_{MAX} for continuous mode of operation from V_{MIN} and V_{OR}.

- Start continuous mode design.
- Recalculate D_{MAX} as:

$$D_{MAX} = \frac{V_{OR}}{V_{OR} + V_{MIN}}$$

Step 15.
Calculate K_{RP} from V_{MIN}, P_O, η, I_P, and D_{MAX}.

- K_{RP} is the ratio between the primary ripple current I_R and primary peak current I_P. And I_P is 90% of minimum I_{LIMIT}.

- From AN-16, $$I_P = \frac{I_{AVG}}{(1-\frac{K_{RP}}{2}) \times D_{MAX}}$$

and $$I_{AVG} = \frac{P_O}{\eta \times V_{MIN}}$$

- By combining the above equations, K_{RP} can be expressed as:

$$K_{RP} = \frac{2 \times (I_P \times D_{MAX} \times \eta \times V_{MIN} - P_O)}{I_P \times D_{MAX} \times \eta \times V_{MIN}}$$

Step 16A, B, C.
Check K_{RP} against 0.6.

- $K_{RP} \geq 0.6$, go to Step 17B.
- $K_{RP} < 0.6$, set $K_{RP} = 0.6$.

  - Recalculate D_{MAX} using Step 15 equation.
  - Recalculate V_{OR} using Step 14 equation.
  - If $V_{OR} < 150$ V, go to Step 17B.
  - If $V_{OR} > 150$ V, go back to Step 7and select higher current *TinySwitch*.

Step 17A, B.
Calculate primary inductance L_P.

- **Discontinuous mode:**

$$L_P = \frac{10^6 \times P_O}{\frac{1}{2} \times \frac{1}{0.9} \times I_P{}^2 \times f_S} \times \frac{Z \times (1-\eta) + \eta}{\eta}$$

- Continuous mode:

$$L_P = \frac{10^6 \times P_O}{K_{RP} \times (1 - \frac{K_{RP}}{2}) \times \frac{1}{0.9} \times I_P{}^2 \times f_S} \times \frac{Z \times (1-\eta) + \eta}{\eta}$$

- I_P is 90% of minimum I_{LIMIT} from *TinySwitch* data sheet as previously defined in Step 8.
- f_S is minimum switching frequency from *TinySwitch* data sheet.
- Please note the cancellation effect between the over temperature variations of I_P and f_S resulting in the additional 1/0.9 term.
- Z is loss allocation factor. If Z = 0, all losses are on the primary side. If Z = 1, all losses are on the secondary side.
- Since output diode loss and clamp/snubber loss are both secondary losses, Z = 1 is a reasonable starting point.

Step 18.
Design Transformer.

- Calculate turns ratio N_P/N_S:

$$\frac{N_P}{N_S} = \frac{V_{OR}}{V_O + V_D}$$

- Selecting core and bobbin

  - With triple insulated secondary wire and no margin winding, EE16 core is suitable for most *TinySwitch* applications.
  - To accommodate margin winding, EEL16 core must be used.
  - In below 2 W and/or space constrained applications, EE13 or EF13 cores with special bobbin meeting safety requirements may be used.

- Calculate primary and secondary number of turns for peak flux density (B_P) not to exceed 3000 gauss. **Limit B_P to 2500 gauss for low audio noise designs.** Use the lowest practical value of B_P for the greatest reduction in auido noise. See AN-24 for additional information.
  - Calculate primary number of turns (N_P)

$$N_P = 100 \times I'_P \times \frac{L_P}{B_P \times A_e}$$

where I'_P equals to maximum I_{LIMIT}

- Calculate secondary number of turns N_S:

$$N_S = \frac{N_P \times (V_O + V_D)}{V_{OR}}$$

- Calculate gap length (L_g). Gap length should be larger than 0.1 mm to ensure manufacturability.

$$L_g = 40 \times \pi \times A_e \left(\frac{N_P^{\ 2}}{1000 \times L_P} - \frac{1}{A_L} \right)$$

- Please refer to Power Integrations Web site ***www.powerint.com*** for audio noise suppression techniques applicable to transformer design.

Step 19A, B. Calculate primary RMS current I_{RMS} and secondary RMS current I_{SRMS}.

- Discontinuous mode:
  - Calculate primary RMS current I_{RMS}

$$I_{RMS} = \sqrt{D_{MAX} \times \frac{I_P'^{\,2}}{3}}$$

where I'_P equals to maximum I_{LIMIT}

  - Calculate secondary RMS current I_{SRMS}

$$I_{SRMS} = I_{SP} \times \sqrt{\frac{1 - D_{MAX}}{3 \times K_{DP}}}$$

where $I_{SP} = I'_P \times \frac{N_P}{N_S}$

and I'_P equals to maximum I_{LIMIT}

- Continuous mode:
  - Calculate primary RMS current I_{RMS}

$$I_{RMS} = I'_P \times \sqrt{D_{MAX} \times \left(\frac{K_{RP}^{\ 2}}{3} - K_{RP} + 1 \right)}$$

where I'_P equals to maximum I_{LIMIT}

  - Calculate secondary RMS current I_{SRMS}

$$I_{SRMS} = I_{SP} \times \sqrt{(1 - D_{MAX}) \times \left(\frac{K_{RP}^{\ 2}}{3} - K_{RP} + 1 \right)}$$

where $I_{SP} = I'_P \times \frac{N_P}{N_S}$

and I'_P equals to maximum I_{LIMIT}

- Choose wire gauge for primary and secondary windings based on I_{RMS} and I_{SRMS}.
- In some designs, a lower guage (larger diameter) wire may be necessary to maintain transformer temperature within acceptable limits during continuous short circuit conditions.
- Do not use wire thinner than 36 AWG to prevent excessive winding capacitance and to improve manufacturability.

Step 20.
Determine output short circuit current I_{OS}.

- Calculate maximum output short circuit current I_{OS} from I'_P and N_P/N_S, where I'_P is the maximum I_{LIMIT} from *TinySwitch* data sheet and N_P/N_S is the turns ratio from Step 18:

$$I_{OS} = I'_P \times \frac{N_P}{N_S} \times k$$

where k is the peak to RMS current conversion factor

- The value of k is determined based on empirical measurements: k = 0.9 for Schottky diode and k = 0.8 for PN junction diode.
- Check I_{OS} against diode DC current rating I_D. If necessary, choose higher current diode (see Table 3).

Step 21.
Determine Output Capacitor C_{OUT}.

- Calculate output ripple current:

$$I_{RIPPLE} = \sqrt{I_{SRMS}^{\ 2} - I_O^{\ 2}}$$

- Choose output capacitor with RMS current rating equal to or larger than output ripple current.
- Use low ESR electrolytic capacitor rated for switching power supply use.
- Examples are LXF series from UCC, PL series from Nichicon, and HFQ series from Panasonic.

Step 22.
Determine feedback circuit and output post filter.

- The output voltage of the *TinySwitch* flyback power supply should be sensed at the first output capacitor, which is before the output post LC filer. This way the output post LC filter is outside the feedback control loop and the resonant frequency of the output post LC filter can be as low as required to meet the output ripple specification requirement.
- Use Zener diode in series with the optocoupler LED.
- Output voltage V_O is determined by

$$V_O = V_Z + V_{LED}$$

where $V_{LED} \approx 1\text{V}$

- Replace the Zener with a TL431 for better output accuracy.
- In non-isolated design, use a bipolar NPN transistor in place of the optocoupler. Replace the LED with the base emitter junction and connect the collector to the ENABLE pin of the *TinySwitch*.

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