IX9908
Design Considerations

1 Introduction

This application note provides general guidelines for designing an off-line LED driver using IXYS Integrated Circuits Division's IX9908. The IX9908 can be configured to drive an external MOSFET device in a quasi-resonant flyback converter power stage that provides a constant current output to a LED string while maintaining a high power factor.

This driver features a high voltage start-up circuit that eliminates the need for a V_{CC} resistor, thereby improving overall power dissipation. In addition, there are multiple safety features such as under-voltage lockout, over-voltage protection, digital soft-start, foldback correction, and cycle-by-cycle peak current limiting. The IX9908 is an excellent choice for many phase-cut dimming and high power-factor correction LED lighting applications.

Figure 1 IX9908 Block Diagram

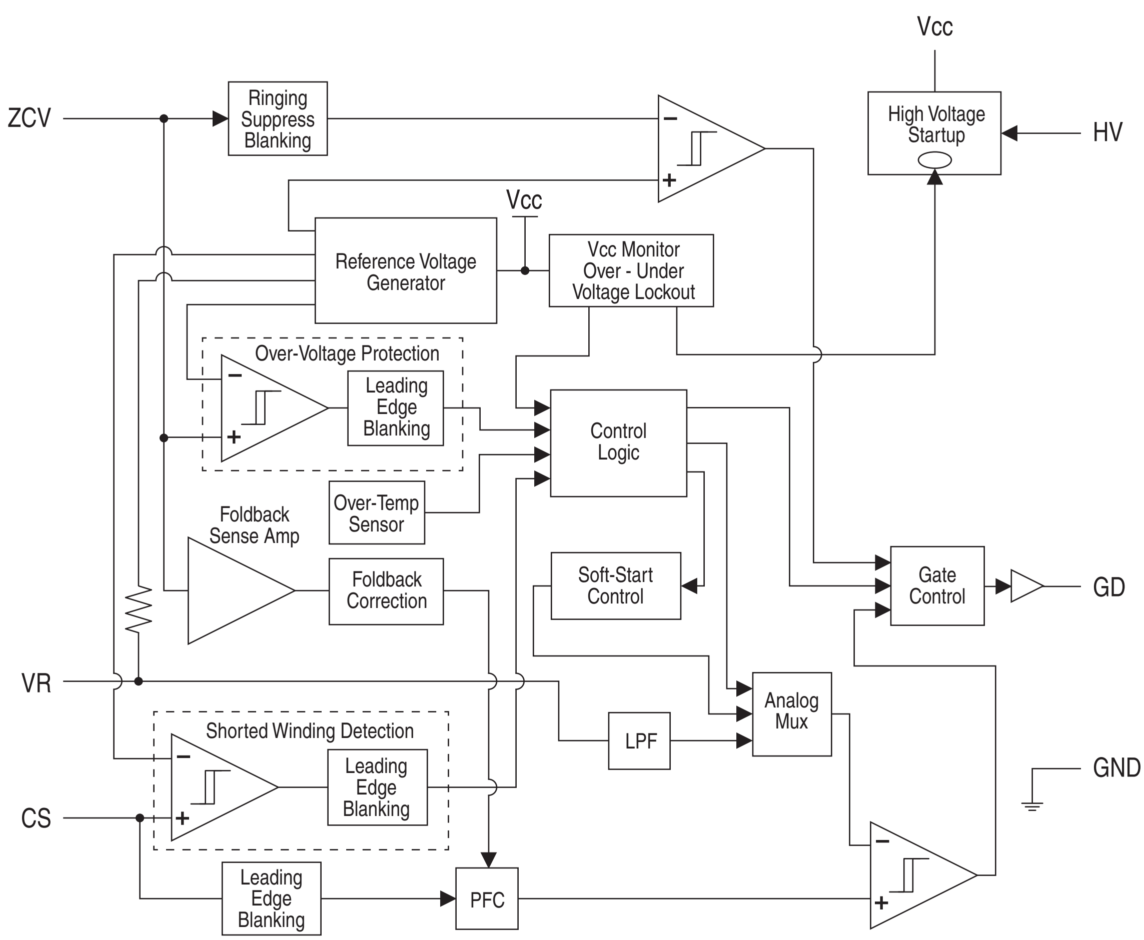
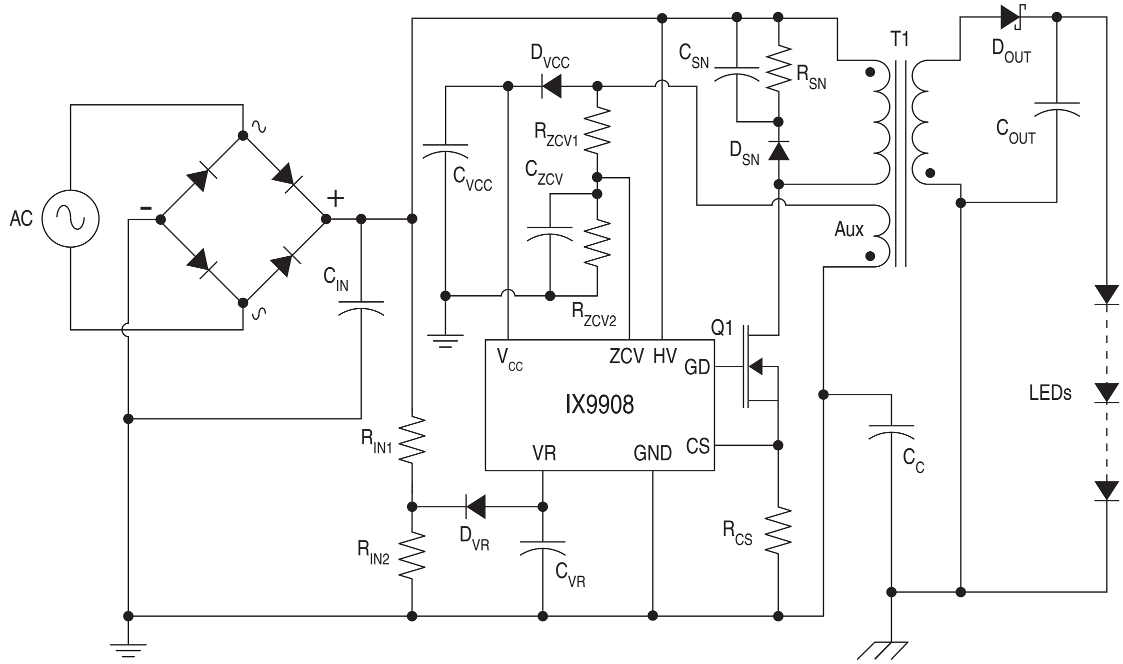


Figure 2 IX9908 Application Circuit



1.1 LED Driver Specifications

The following equations and component selections are based on the following LED driver specifications:

Parameter	Symbol	Rating	Units
AC Input Voltage			
Minimum Voltage	V_{AC_min}	90	V_{rms}
Maximum Voltage	V_{AC_max}	135	
AC Input Frequency	f_{AC}	60	Hz
Auxiliary Voltage	V_{aux_max}	18	V
Auxiliary Current	I_{aux_max}	30	mA
LED String Voltage	$V_{LEDstring}$	20	V
LED String Current	I_{LED_max}	500	mA
Estimated Efficiency	η	85	%
Oscillator Frequency	f_S	67	kHz
Power Factor	PF	98	%
Maximum Duty Cycle	D_{max}	50	%

2 Component Selection

2.1 DC Bulk Voltage at Low and High Line

$$V_{DC\_bulk\_min} = \sqrt{2} \bullet V_{AC\_min} = \sqrt{2} \bullet 90V_{AC} \approx 127.3V$$

$$V_{DC\_bulk\_max} = \sqrt{2} \bullet V_{AC\_max} = \sqrt{2} \bullet 135V_{AC} \approx 191V$$

2.2 Output Power Calculation

$$P_{out} = V_{LEDstring} \bullet I_{LED\_max}$$

$$P_{out} = 20V \bullet 500mA = 10W$$

2.3 Input Power Calculation

$$P_{in} = \frac{P_{out}}{\eta \bullet PF}$$

$$P_{in} = \frac{10W}{0.85 \bullet 0.98} \approx 12W$$

2.4 Primary Inductor Currents Calculation

$$I_{pri\_peak} = \frac{\sqrt{2} \bullet V_{AC\_min} \bullet D_{max}}{L_{pri} \bullet f_S}$$

$$I_{pri\_peak} = \frac{127.3V \bullet 0.5}{1.82mH \bullet 67kHz} \approx 0.522A_{peak}$$

For L_{pri}, see **3.1 Primary Inductance Calculation**.

$$I_{rms} = I_{pri\_peak} \bullet \sqrt{\frac{D_{max}}{3}}$$

$$I_{rms} = 0.522A_{peak} \bullet \sqrt{\frac{0.5}{3}} \approx 0.213A_{rms}$$

Note that duty cycle above 50% will result in converter stability issues such as sub-harmonic oscillations.

2.5 Reflected Flyback Voltage Calculation

$$V_{ro} = \frac{V_{LEDstring} + V_f}{\left(\frac{N_S}{N_P}\right)} = \frac{20V + 0.7V}{0.1626} \approx 127V$$

See **3.2 Determine Transformer Turns Ratio** for N_S/N_P ratio.

2.6 Input Capacitor, C_{IN}

The IX9908 is designed to operate without the need of a large bulk capacitor. This operating method enables the input current to form a triangular shape that closely follows the rectified AC line voltage, enabling a very high power factor of up to 98% with low total harmonic distortion (THD).

A small, 0.1μF, 400V polyester film filter capacitor should be adequate for this application.

2.7 Input Rectifier Bridge

The breakdown voltage for this bridge is based on the maximum input voltage.

$$V_{bridge} = \sqrt{2} \bullet 135V_{AC} \bullet 2 \approx 382V$$

Select the next higher standard voltage, 400V.

The rectifier bridge is exposed to high surge currents, so select a bridge that can handle at least five times the I_{rms} input current. In this case, a 1A bridge would be sufficient.

2.8 Calculate MOSFET Voltage Rating

$$V_{DS} = V_{DC\_bulk\_max} + V_{ro} + V_{spike}$$

Assume that V_{spike}=50V.

$$V_{DS} = 191V + 127V + 50V \approx 368V$$

Due to the voltage spikes resulting from leakage inductance, the MOSFET should be selected with an adequate margin. A good choice would be between 500V and 600V.

2.9 Design RCD Snubber

In a flyback topology, a snubber circuit is required to clamp the voltage caused by the leakage inductance, which is present in all transformers. Leakage inductance is highly dependent on the transformer construction, so care should be taken to keep it less than 2% of primary inductance. When no leakage inductance is known, a leakage inductance value of 37μH (2% of 1.82mH) can be used as a starting point to calculate the snubber's resistor, capacitor, and diode values.

D_{SN} is selected as 1N4007GP (1000V, 1A axial lead).

Energy stored in the leakage inductance L_e:

$$W1 = 0.5L_e \bullet I_{rms}^2 = 0.5 \bullet 37\mu H \bullet 0.213^2 \approx 0.84\mu J$$

Average power transferred from W1 to the snubber:

$$P1 = W1 \bullet f_S = 0.84\mu J \bullet 67kHz \approx 56mW$$

$$V_{max} = V_{DC\_bulk\_max} + V_{ro} + V_{spike}$$

$$V_{max} = 191V + 127V + 50V = 368V$$

- V_{spike} = 50V
- V_{ro} = 127V

Limiting the voltage to 368V.

$$V_{SN} = 368V - 127V = 241V$$

$$R_{SN} = \frac{V_{SN}^2}{P1} = \frac{241V^2}{0.056W} \approx 1M\Omega$$

$$C_{SN} = \frac{T_S}{R_{SN}} = \frac{15\mu s}{1M\Omega} = 0.015nF$$

$$C_{SN} \gg \frac{T_S}{R_{SN}} = \frac{1}{f_S \bullet R_{SN}} = \frac{1}{67kHz \bullet 1M\Omega} \approx 15pF$$

For margin, C_{SN} =1nF is selected. This value is a starting point, and might have to be adjusted to get the desired voltage spike suppression.

2.10 Over-Voltage Protection & Zero-Crossing Detection

The application schematic in **Figure 2 IX9908 Application Circuit** shows that the voltage from the auxiliary winding is connected to the zero crossing pin (ZCV), via RC network resistor R_{ZCV1}, R_{ZCV2} and C_{ZCV}. The circuit provides a delay so that switch-on can occur at the voltage valley, thus enhancing efficiency. The line voltage is sensed indirectly through the current in R_{ZCV1}.

The current equation is given by:

$$I_{ZCV} = \frac{V_{DC\_bulk\_min} \bullet N_A}{R_{ZCV1} \bullet N_P}$$

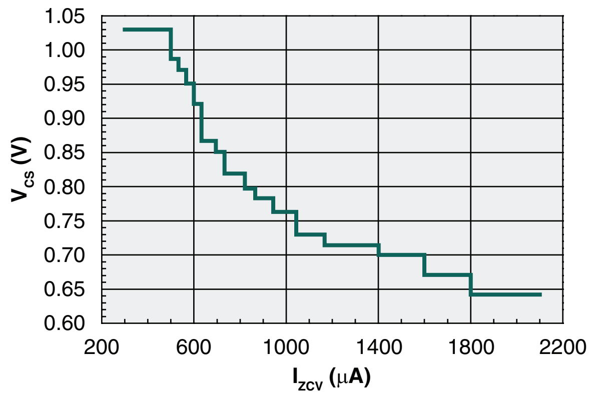
Solving for R_{ZCV1}:

$$R_{ZCV1} = \frac{V_{DC\_bulk\_min}}{I_{ZCV}} \bullet \frac{N_A}{N_P}$$

From the V_{CS} vs. I_{ZCV} graph below we select I_{ZCV} = 1000µA as the recommended current.
For N_A/N_P value, see **3.2 Determine Transformer Turns Ratio**.

$$R_{ZCV1} = \frac{127.3V}{0.001A} \bullet 0.1468 \approx 18.7k\Omega$$

Figure 3 V_{CS} vs. I_{ZCV}



The over voltage detection can be programmed by R_{ZCV2} resistor. The output, $V_{LEDstring}$, is 20V, so select an over voltage protection of 35V, and from the datasheet, V_{ZCVOVP} = 3.7V

$$R_{ZCV2} = \frac{R_{ZCV1} \bullet V_{ZCVOVP}}{V_{oovpth} - V_{ZCVOVP}}$$

$$R_{ZCV2} = \frac{18.7k\Omega \bullet 3.7V}{35V - 3.7V} \approx 2.210k\Omega$$

The delay capacitor can be approximated:

$$C_{ZCV} = t_{RC} \bullet \frac{R_{ZCV1} + R_{ZCV2}}{R_{ZC1} \bullet R_{ZC2}}$$

$$C_{ZCV} = 1\mu s \bullet \left(\frac{18.7k\Omega + 2.210k\Omega}{18.7k\Omega \bullet 2.210k\Omega}\right) \approx 519pF$$

Where t_{RC} = 1µs (see IX9908 data sheet).

2.11 Primary Peak Current Control

The value of the current sense resistor (R_{CS}) can be selected by using following equation:

$$R_{CS} = \frac{V_{CSmax}}{I_{pri\_peak}}$$

$$R_{CS} = \frac{0.75V}{0.522A_{peak}} \approx 1.44\Omega$$

The R_{IN1} and R_{IN2} resistor values can be selected to scale the input voltage at the V_R pin. The R_{IN1} resistor is selected with consideration of losses and high power factor correction. In this example we select R_{IN1} = 1046kΩ. Select two 523kΩ standard value resistors in the 0805 package.

The R_{IN2} value can be calculated:

$$R_{\mathrm{IN2}} = \frac{R_{\mathrm{IN1}} \bullet R_{\mathrm{CS}} \bullet G_{\mathrm{PWM}} \bullet I_{\mathrm{pri\_peak}}}{V_{\mathrm{DC\_bulk\_min}} - (G_{\mathrm{PWM}} \bullet I_{\mathrm{pri\_peak}} \bullet R_{\mathrm{CS}})}$$

R_{IN2} = 18.8kΩ. Select a standard value resistor, 18.7kΩ, where:

PWM-Op gain, G_{PWM} = 3 (from the IX9908 data sheet).

Select the C_{VR} capacitor to be 2.2nF and the D_{VR} diode can be BAS16, 100V, or equivalent.

2.12 Selection of V_{CC} Capacitor and Auxiliary Blocking Diode

In this application, a simple and inexpensive power supply for the IC is made from the auxiliary winding by using a blocking diode and a capacitor.

The auxiliary V_{CC} diode blocking voltage can be calculated:

$$V_{\mathrm{DVcc}} > \left(\sqrt{2} \bullet V_{\mathrm{AC\_max}} \bullet \frac{N_{\mathrm{A}}}{N_{\mathrm{P}}}\right) + V_{\mathrm{aux\_max}}$$

$$V_{\mathrm{DVcc}} > (191\,V \bullet 0.1468) + 18\,V \approx 46\,V$$

In this case, BAS16, 100V, or equivalent, would be selected.

For a dimming application a 22µF capacitor would be required: if there is no dimming requirement, then a 10µF capacitor will suffice.

2.13 Output Schottky Diode and Capacitor

The Schottky output diode is exposed to large currents when the converter is operated in critical conduction mode, CCM. Care should be taken to ensure adequate margins for the voltage and current ratings.

The required blocking voltage for D_{OUT}:

$$V_{\mathrm{d\_out}} > \left(\sqrt{2} \bullet 135\,V_{\mathrm{AC\_max}} \bullet \frac{N_{\mathrm{S}}}{N_{\mathrm{P}}}\right) + V_{\mathrm{LEDstring}}$$

$$V_{\mathrm{d\_out}} > (191\,V \bullet 0.1626) + 20\,V \approx 51\,V$$

See **3.2 Determine Transformer Turns Ratio** for the N_S/N_P ratio. Select a Schottky diode with a 150V rating.

The output diode is exposed to large peak currents.

$$I_{\mathrm{d\_rms}} = I_{\mathrm{rms}} \bullet \sqrt{\frac{1 - D_{\mathrm{max}}}{D_{\mathrm{max}}}} \bullet \frac{V_{\mathrm{ro}}}{V_{\mathrm{LEDstring}} + V_{\mathrm{f}}}$$

$$I_{\mathrm{d\_rms}} \approx 0.213\,A_{\mathrm{rms}} \bullet 1 \bullet 6.135 = 1.31\,A_{\mathrm{rms}}$$

See **2.4 Primary Inductor Currents Calculation**. For adequate margin, select a $3A_{rms}$ diode, such as STPS3150V.

The output capacitor can be selected based on the desired output voltage ripple. The dynamic resistance of the LED driven at a given current should also be considered, as this will determine the current ripple through the LED string.

In this application, the LEDs have a dynamic resistance of 1Ω measured at 500mA operating current. 6 LEDs result in 6Ω of dynamic resistance.

$$V_{\mathrm{out\_rip}} = I_{\mathrm{LED\_max}} \bullet R_{\mathrm{dynamic}}$$

$$V_{\mathrm{out\_rip}} = 500\,mA \bullet 6\Omega = 3\,V_{\mathrm{PP}}$$

The output capacitor can be approximated:

$$C_{\mathrm{out}} = \frac{2 \bullet I_{\mathrm{LED\_max}}}{V_{\mathrm{out\_rip}} \bullet 2 \bullet \pi \bullet 120\,Hz}$$

$$C_{\mathrm{out}} = \frac{2 \bullet 500\,mA}{3\,V_{\mathrm{PP}} \bullet 2 \bullet \pi \bullet 120\,Hz} \approx 442\,\mu F$$

Select two 220µF capacitors, EEV-FM1V221L. These capacitors are rated at 105°C for 4000 hours with 100kHz frequency.

3 Transformer Design

A step-by-step guide for transformer design will be presented here. Primary inductance and turns ratio will be calculated, and the appropriate wire size will be selected. The transformer core and coil former will be selected to support design power requirements, and a general guideline will be presented for transformer construction to achieve the best efficiency, and avoiding transformer saturation at higher temperatures.

3.1 Primary Inductance Calculation

$$L_{pri} = \frac{(V_{DC\_bulk\_min} \bullet \eta \bullet D_{max})^2}{2 \bullet P_{IN} \bullet F_S}$$

$$L_{pri} = \frac{(127.3V \bullet 0.85 \bullet 0.5)^2}{2 \bullet 12W \bullet 67kHz} \approx 1.82mH$$

3.2 Determine Transformer Turns Ratio

$$\frac{V_{LEDstring}}{V_{IN}} = \frac{N_S}{N_P} \bullet \frac{D_{max}}{1 - D_{max}}$$

Secondary to primary turns ratio:

$$\frac{N_S}{N_P} = \frac{V_{LEDstring} + V_f}{\sqrt{2} \bullet V_{AC\_min}} \bullet \frac{1 - D_{max}}{D_{max}}$$

Where V_f is the voltage drop of the output diode.

$$\frac{N_S}{N_P} = \frac{20V + 0.7V}{\sqrt{2} \bullet 90V} \bullet \frac{1 - 0.5}{0.5} \approx 0.1626$$

The auxiliary to primary turns ratio:

$$\frac{N_A}{N_P} = \frac{V_{aux\_max} + V_f}{\sqrt{2} \bullet V_{AC\_min}} \bullet \frac{1 - D_{max}}{D_{max}}$$

$$\frac{N_A}{N_P} = \frac{18V + 0.7V}{\sqrt{2} \bullet 90V} \bullet \frac{1 - 0.5}{0.5} \approx 0.1469$$

The auxiliary to secondary turns ratio:

$$\frac{N_A}{N_S} = \frac{V_{aux\_max} + V_f}{V_{LEDstring} + V_f}$$

$$\frac{N_A}{N_S} = \frac{18V + 0.7V}{20V + 0.7V} \approx 0.9034$$

3.3 Determine Primary Winding Wire Size

The first step is to find the RMS current through the primary winding, which can be approximated with the following equation:

$$I_{rms} = I_{pri\_peak} \bullet \sqrt{\frac{D_{max}}{3}}$$

$$I_{rms} = 0.522A_{peak} \bullet \sqrt{\frac{0.5}{3}} \approx 0.213A_{rms}$$

The primary winding wire area can be calculated:

$$A_{w\_pri} = \frac{I_{rms}}{J_{max}} \approx \frac{0.213A_{rms}}{6A/mm^2} = 0.0355mm^2$$

Where J_{max} is the current density of a wire, which is stated by the wire manufacturer to be 6A/mm^2.

The diameter is determined by the following formula:

$$\text{Wire Diameter} = 2 \bullet \sqrt{\frac{A_W}{\pi}} = \sqrt{\frac{A_W}{\pi/4}} \approx \sqrt{\frac{A_W}{0.7854}}$$

$$D_{w\_pri} \approx \sqrt{\frac{0.0355mm^2}{0.7854}} \approx 0.213mm$$

From **Table 1: Wire Gauge Table** this is converted to 32 AWG.

3.4 Determine Secondary Winding Wire Size

The peak current of secondary winding can be determined by the following formula:

$$I_{sec\_peak} = \frac{2 \bullet I_{LEDmax}}{1 - D_{max}} = \frac{2 \bullet 0.5A}{1-0.5} = 2A_{peak}$$

The RMS current can be found:

$$I_{sec\_rms} = I_{sec\_peak} \bullet \sqrt{\frac{1 - D_{max}}{3}} \approx 2A_{peak} \bullet 0.408 \approx 0.817A_{rms}$$

Calculate the secondary wire size:

$$A_{w\_sec} = \frac{I_{sec\_rms}}{6} \approx \frac{0.817A_{rms}}{6} \approx 0.136mm^2$$

Calculate the secondary wire diameter:

$$D_{w\_sec} \approx \sqrt{\frac{0.136mm^2}{0.7854}} \approx 0.416mm$$

Convert using **Table 1: Wire Gauge Table** to AWG 26.

3.5 Determine Auxiliary Winding Wire Size

The maximum current in the auxiliary winding can be calculated using:

$$I_{\text{aux\_peak}} = \frac{2 \bullet I_{\text{aux\_max}}}{1 - D_{\text{max}}} = \frac{2 \bullet 30mA}{1 - 0.5} = 0.12A_{\text{peak}}$$

The RMS current can be calculated:

$$I_{\text{aux\_rms}} = I_{\text{aux\_peak}} \bullet \sqrt{\frac{1 - D_{\text{max}}}{3}} \approx 0.049A_{\text{rms}}$$

The required wire area is given:

$$A_{\text{w\_aux}} = \frac{I_{\text{aux\_rms}}}{6} \approx 0.0082mm^2$$

Wire diameter:

$$D_{\text{w\_aux}} \approx \sqrt{\frac{0.0082mm^2}{0.7854}} \approx 0.102mm$$

Convert using **Table 1: Wire Gauge Table** to AWG 38.

Table 1: Wire Gauge Table

American Wire Gauge (AWG)	Equivalent Wire Diameter (mm)	Equivalent Wire Area (mm^2)
40	0.0799	0.00501
39	0.0897	0.00632
38	0.101	0.00797
37	0.113	0.01
36	0.127	0.0127
35	0.143	0.016
34	0.16	0.0201
33	0.18	0.0254
32	0.202	0.032
31	0.227	0.0404
30	0.255	0.051
29	0.286	0.0642
28	0.321	0.081
27	0.361	0.102
26	0.405	0.129
25	0.455	0.162
24	0.511	0.205
23	0.573	0.258
22	0.644	0.326
21	0.723	0.41
20	0.812	0.518
19	0.912	0.653
18	1.024	0.823
17	1.15	1.038
16	1.29	1.31
15	1.45	1.65
14	1.63	2.08
13	1.83	2.62
12	2.05	3.31
11	2.3	4.17
10	2.59	5.26
9	2.91	6.63
8	3.26	8.37
7	3.67	10.55
6	4.11	13.3
5	4.62	16.75
4	5.19	21.15
3	5.83	26.67
2	6.54	33.62
1	7.35	42.4

3.6 Select Inductor Core & Calculate Turns

The Ferroxcube catalog lists the following specifications for the E20/10/5 core set.

- $\Sigma(l_e/A_e)$ core factor = 1.37 mm^{-1}
- V_e effective volume = 1340 mm^3
- l_e effective length = 42.8 mm
- A_e effective area = 31.2 mm^2

The air gap, G, of 0.3mm may be used for initial calculation. The effective permeability of the core can be calculated:

$$\mu_e = \frac{\mu_i}{1 + \frac{G \bullet \mu_i}{l_e}}$$

Where μ_i = 2000 (for N27 material or 1P2400) and G=0.3mm.

$$\mu_e = \frac{2000}{1 + \frac{0.3mm \bullet 2000}{42.8mm}} \approx 133$$

Calculate Inductance Factor A_L for this core:

$$A_L = \frac{\mu_o \bullet \mu_e}{\sum \frac{l_e}{A_e}}$$

$$A_L \approx \frac{4\pi \bullet 10^{-7}\text{H} \bullet 133}{m \bullet turn^2} \bullet \frac{10^{-3}}{1.37} \approx \frac{121.99\text{nH}}{turn^2}$$

Where μ_0 = vacuum permeability = 4 π*10^{-7}H/m.

Calculate number of turns for the primary winding:

$$N_{pri} = \sqrt{\frac{L_{pri}}{A_L}} \approx \sqrt{\frac{1.82mH}{121.99\text{nH}} \bullet turn^2} \approx 122 \text{ turns}$$

Calculate the maximum flux density:

$$B_{max} = N_{pri} \bullet I_{pri\_peak} \bullet \frac{A_L}{A_e}$$

$$B_{max} \approx \frac{122turn \bullet 0.522A_{peak} \bullet \frac{121.99nH}{turn^2}}{31.2mm^2} \approx 0.248T$$

Note that B_{max} for 1P2400, MnZn ferrite, is 0.36T at 100°C.

Calculate number of turns for secondary and auxiliary windings:

$$N_{sec} = N_{pri} \bullet \frac{N_S}{N_P} \approx 122turns \bullet 0.1626 \approx 20 \text{ turns}$$

$$N_{aux} = N_{pri} \bullet \frac{N_A}{N_P} \approx 122turns \bullet 0.1468 \approx 18 \text{ turns}$$

Calculate to make sure windings will fit the winding area of coil former. The Ferroxcube data sheet provides information for 8-pin coil former and specifies winding area of 27mm^2.

The fill factor has to be taken into consideration as this will affect winding area for this coil former. In general we can use fill factor Ku of 0.3 to 0.7 as a starting point. In this case 0.3 will be selected.

$$\text{Total Winding Area} = \frac{1}{Ku} \bullet [(N_{pri} \bullet A_{w\_pri}) + (N_{sec} \bullet A_{w\_sec}) + (N_{aux} \bullet A_{w\_aux})] \le 27mm^2$$

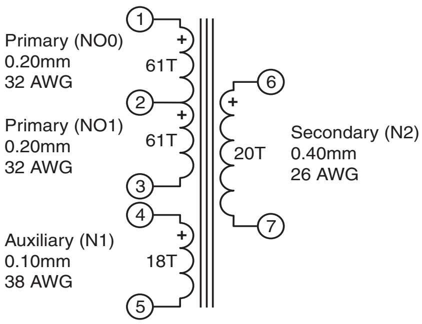
$$\text{Total Winding Area} \approx 3.33 \bullet [(122 \bullet 0.0355mm^2) + (20 \bullet 0.136mm^2) + (18 \bullet 0.0081mm^2)] \le 27mm^2$$

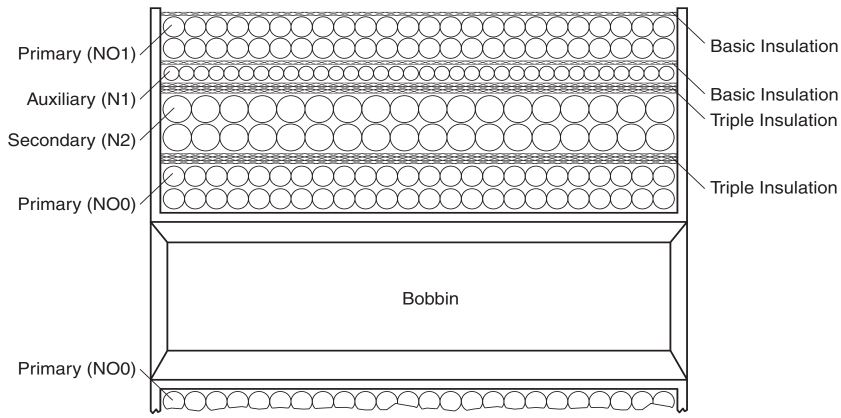
$$\text{Total Winding Area} \approx 24mm^2 \le 27mm^2$$

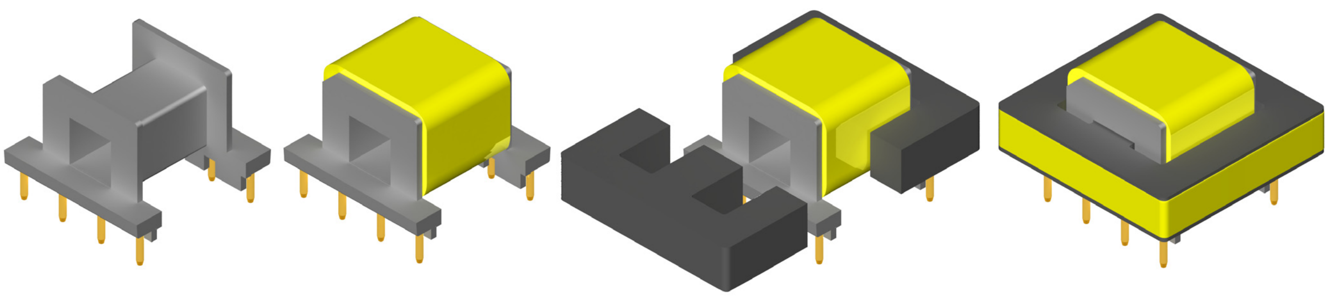
Note: The total winding area should not be exceeded due to the selection of approximate standard wire gauges from **Table 1: Wire Gauge Table**.

3.7 Flyback Transformer Construction

The transformer block diagram shows the primary split into two sections of 61 turns each. The secondary and auxiliary are wound between the two primary windings. The transformer stack-up has three layers of insulation tape between the primary and the secondary side. This method enables the transformer to pass the safety standard for electrical strength requirement. In the previous step, we selected an air gap of 0.3mm as our starting point. The air gap is critical because it allows the transformer to extend its maximum saturation; however, if the gap is larger, then it could contribute to higher leakage inductance. In this example, it is possible to achieve a leakage inductance less than 2% of primary.







Bobbin

Coils wound on bobbin & insulated with XFMR tape

Installation of ferrite core halves

Core halves secured with XFMR tape

For additional information please visit our website at: www.ixysic.com

Specification: AN-302-R03

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