Automotive Headlamp HID Ballast Reference Design Using the dsPIC® DSC Device

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INTRODUCTION

In recent years, High Intensity Discharge (HID) lamps have been accepted as a good lighting source for automotive headlight applications. However, the start-up process of an automotive HID lamp is complex. It consists of six stages and each stage presents different characteristics, which need different control strategies.

A digitally controlled ballast has many advantages over the traditional analog approach:

- Convenient implementation of sophisticated control algorithms
- High performance operation
- Effective protection
- Very robust
- Low cost

This application note focuses on the implementation of an automotive HID electronic ballast using a Microchip GS-series 16-bit Digital Signal Controller (DSC).

HID Lamp

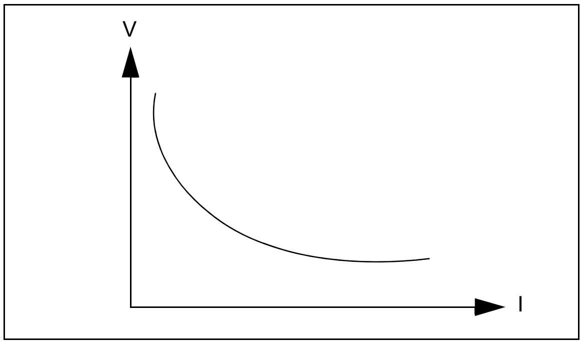
Gas is a good insulator under normal conditions. However, special conditions such as a strong electric field, x-ray radiation, ion bombardment, and high temperature heat could lead to ionization of gas molecules and produce free-charged particles. These charged particles can conduct current under an electric field, which is known as gas discharge.

The light source made by this principle is called a gas discharge lamp. A HID lamp is one kind of gas discharge lamp. Others include high-pressure mercury lamps, high-pressure sodium lamps, metal halide lamps and some rare gas lamps, such as Xenon and Krypton lamps.

HID lamps have many advantages over incandescent and fluorescent lighting, such as long lamp life, high efficiency, high brightness and low power consumption. They are widely used in factory buildings, airports, stadiums and square-shaped lighting fixtures. In addition, Xenon lamps are widely used in automotive applications.

Compared with conventional halogen lamps, Xenon lamps have features of high luminous efficacy, low power consumption, good color rendering and long lamp life. Xenon lamp automotive headlamp systems greatly improve the safety of driving at night.

FIGURE 1: VOLTAGE AND CURRENT OF HID LAMPS AT STEADY STATE



HID Electronic Ballast

HID lamps present a negative resistance characteristic, which is shown in Equation 1.

EQUATION 1: NEGATIVE RESISTANCE CHARACTERISTIC

$$\frac{dV_{lamp}}{dI_{lamp}} < 0$$

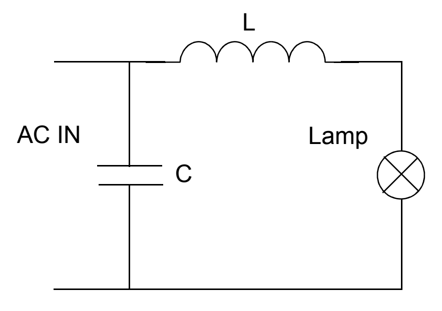
This means the ballast is unstable if the lamp was directly connected to a voltage source. A series positive impedance is needed to ensure the ballast has a positive resistance characteristic, as shown in Equation 2. This is the basic ballast principle.

EQUATION 2: POSITIVE RESISTANCE CHARACTERISTIC

$$\frac{dV_{system}}{dI_{system}} > 0$$

A traditional inductive ballast shown in Figure 2 has many problems such as large bulk capacitors, low Power Factor (PF) and difficulty reigniting. An electronic ballast is used to control the lamp current and lamp output power. Instant start-up, small size, high PF, and high efficiency can be achieved using an electronic ballast.

FIGURE 2: INDUCTIVE BALLAST



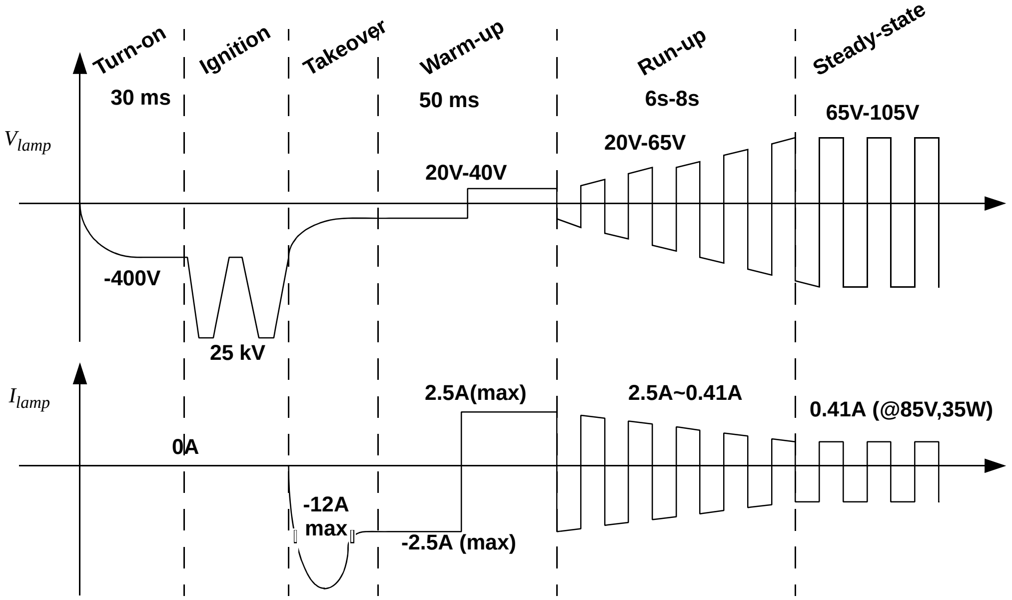
Good electronic ballasts must have the following important features:

- High power factor, greater than 0.9 at the ballast input
- THD should be limited below 33%
- No flicker during the lamp start-up process
- High power efficiency
- No acoustic resonance

Technical Background of Automotive HID Ballast

The start-up process of automotive HID lamps is quite complex. Figure 3 shows the working profile of HID lamp voltage and current during the start-up process. This is the inherent characteristic of an HID lamp and the ballast must be designed to meet this profile; otherwise, the HID lamp will not operate as expected.

FIGURE 3: AUTOMOTIVE HID LAMP VOLTAGE AND CURRENT



Note: The data presented in this figure depends on the lamp part number and working conditions.

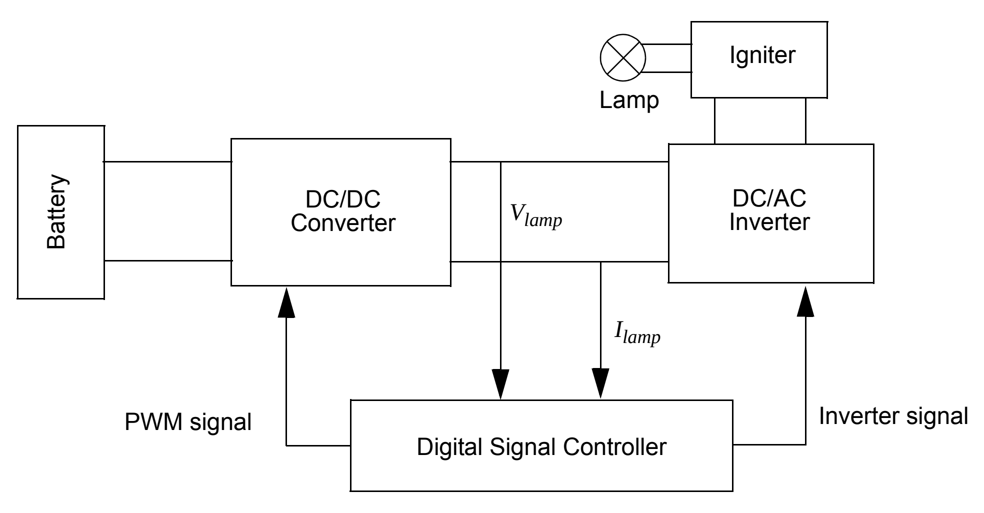
- **Turn-on:** Before ignition, the lamp's equivalent impedance is considered as infinite, so the ballast is treated as an open circuit. In this stage, the ballast produces adequate voltage. In this stage, the voltage generated by the ballast is fed to the igniter circuitry to ignite the lamp.
- **Ignition:** Automotive HID lamps are high pressure gas lamps. During this stage, the igniter circuitry generates a high voltage pulse across the lamp and the lamp transfers from isolation status to current conductive status. As the result, an arc is established in the tube and visible light is generated. The required ignition voltage for a hot lamp is around 25 kV. For a cold lamp, the voltage is around 10 kV.
- **Takeover:** After successful ignition, the lamp requires a large current (takeover current) to sustain the arc. The output capacitance and auxiliary current circuit can provide this high magnitude current before the DC/DC converter delivers enough power to the lamp.
- **Warm-up:** In this stage, the DC/DC converter provides a certain amount of current, depending on the lamp condition to sustain the arc. The converter works as current mode, and generates a square wave AC current. As the frequency is small (20 Hz) when compared to steady-state, it's also called DC status.
- **Run-up:** This is the key stage of the start-up process. In order to meet the SAE J2009 and ECE Reg. No 99 specification for the light output versus time, the start transient power of the lamp is much higher than the steady state. Then, the ballast controls the lamp power to ramp down to the normal level.
- **Steady State:** The lamp voltage is ~ 85V, and the lamp current is ~0.4A, depending on lamp conditions. But the lamp power is recommended to be 35W, ±1W. This helps to ensure better output light performance and longer lamp life.

The ballast in this reference design consists of four sections, as shown in Figure 4:

- High frequency DC/DC converter
- Low frequency DC/AC inverter
- Ignition circuit
- Digital Signal Controller

The DC/DC converter boosts the battery voltage (9V-16V) to a high level for the ignition circuit first, and then drops to ~85V for steady state operation. The DC/AC inverter converts the DC current to a square wave current to energize the two lamp electrodes equally. The high voltage igniter generates high voltage pulses to strike the lamp. Both The DC/DC converter and the DC/AC inverter are controlled by a single digital signal controller.

FIGURE 4: BLOCK DIAGRAM OF THE DIGITAL REFERENCE DESIGN AUTOMOTIVE HID BALLAST



AUTOMOTIVE HID BALLAST DIGITAL DESIGN

System Design Specifications

Table 1 lists the system specifications used for the automotive HID ballast digital design.

TABLE 1: SYSTEM DESIGN SPECIFICATIONS

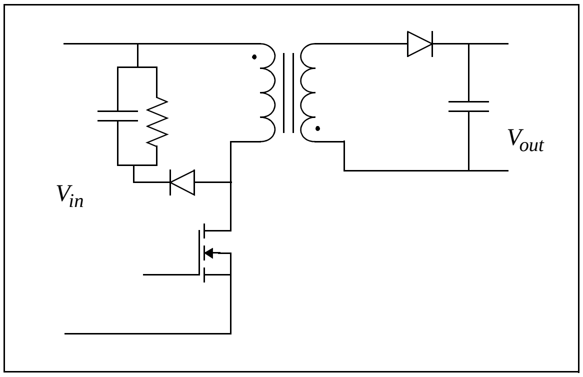
Characteristic		Specification	Conditions
Input Voltage	Nominal	13.5V	—
	Operation	9V-16V	
Temperature Range	Operation	-40°C to 105°C	
Transient	Maximum input current	Cold lamp: 12A Hot lamp: 4A	
	Maximum output current	2.5A	
	Maximum input power	115W	13.5V, 25°C
			9V-16V, -40°C to 105°C
	Maximum output power	75W	13.5V, 25°C
			9V-16V, -40°C to 105°C
	Light output	Meet ECE R99	13.5V, 25°C
Steady	Input current	3.5A maximum	13.5V, -40°C to 105°C
	Output power	35W ±1W	9V-16V, -40°C to 105°C
	Time of steady light output	≤150s	13.5V, 25°C
	Efficiency	> 85%	13.5V
Acoustic Resonance	—	No acoustic resonance	—
Flicker	—	No flicker	
Reliability	Restrike	100%	100 times turn-on/off
	Successive operation	3000 hours	—
Input Protection	Undervoltage protection	9V	
	Overvoltage protection	16V	
Output Protection	Short-circuit protection	Yes	
	Open circuit protection	Yes	
Dimension	—	≤10 mm * 60 mm * 80 mm	
EMI	—	Meet ECE R10 (error < 20%)	

Hardware Topology Selection

DC/DC CIRCUIT

The DC/DC converter is the key stage to implement the control of the lamp voltage, lamp current, and lamp power. The performance and efficiency of the ballast are dependent on this stage. As introduced previously, this stage must have a boost function and large voltage output capability for open load. The flyback topology shown in Figure 5 is selected for the minimum number of components. In addition, voltage and current stress on the switch is decreased due to the boost function of the flyback transformer. However, the leakage inductance of the transformer will generate a high-voltage pulse on the switch, which affects system power efficiency.

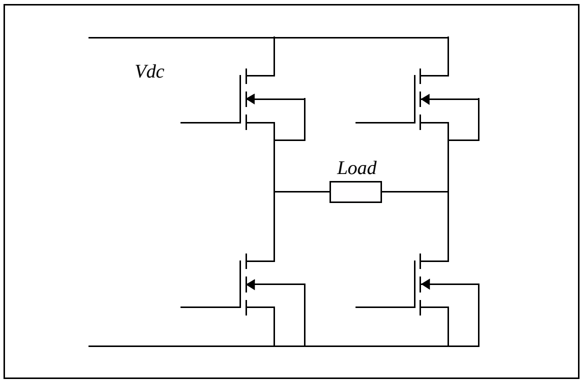
FIGURE 5: FLYBACK DC/DC CONVERTER



DC/AC CIRCUIT

A full-bridge inverter is selected for this stage. Figure 6 shows the full-bridge inverter topology. The operation frequency of the inverter is dependent on the lamp state. Before ignition, the inverter runs at a frequency of 1 kHz for the turn-on and ignition stages. After ignition, the operation frequency is only 20 Hz for the warm-up stage. When the warm-up stage is over, the inverter operates at 200 Hz.

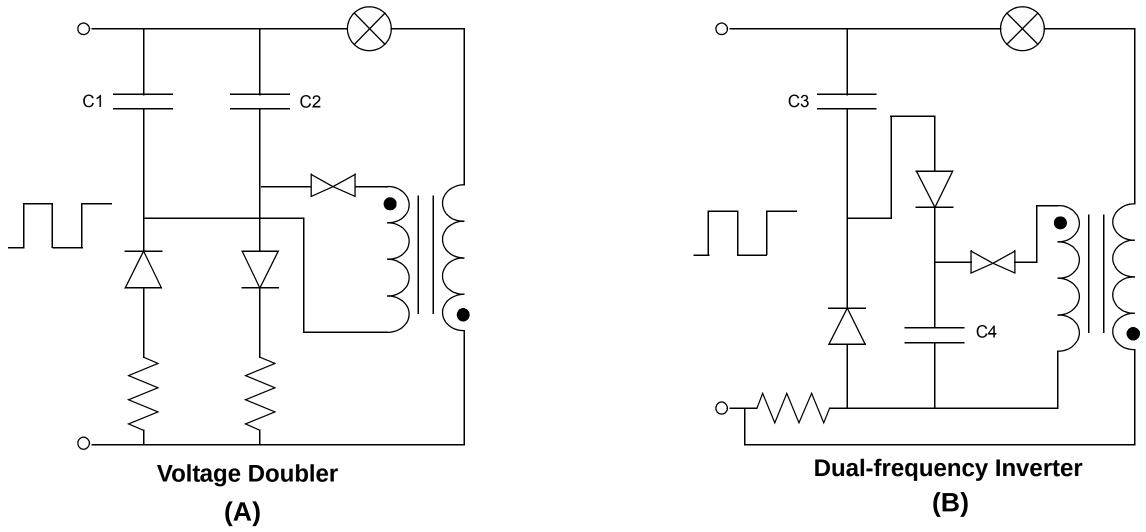
FIGURE 6: FULL-BRIDGE INVERTER



IGNITION CIRCUIT

The automotive HID ballast adopts an ignition circuit, which is driven by a dual-frequency inverter, as shown in Figure 7(B). Compared to a conventional ignition circuit with a voltage doubler, which is shown in Figure 7(A), it has two main advantages: the first is that the large ignition capacitor, C1, can be replaced by a much smaller one (C3 ≤ C1/10), and the second is it can generate a higher power pulse. This improves the ignition success rate especially for a hot lamp strike.

FIGURE 7: IGNITION CIRCUITS



Voltage Doubler
(A)

Dual-frequency Inverter
(B)

DIGITAL SIGNAL CONTROLLER

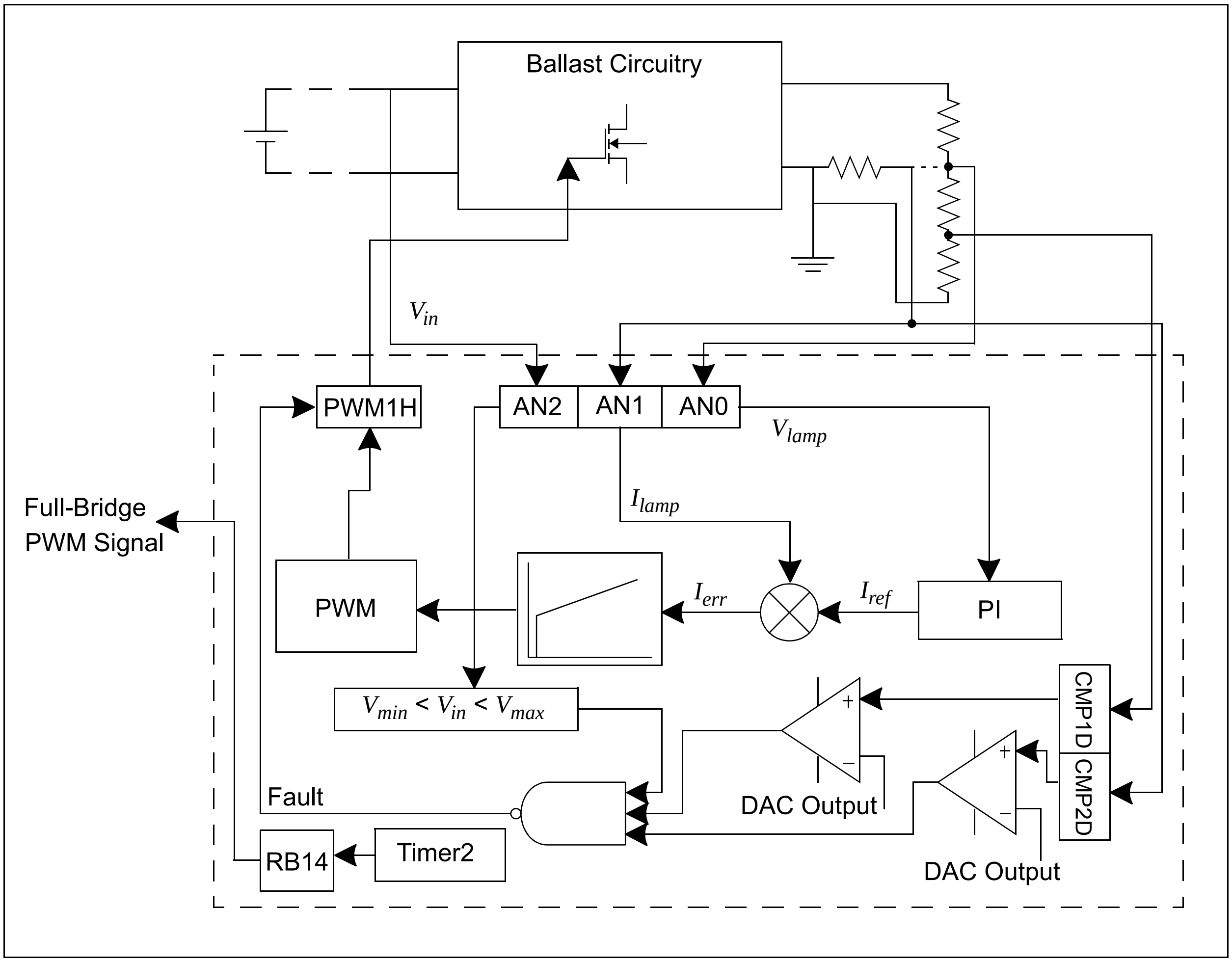
The dsPIC DSC detects the lamp voltage and lamp current through the Analog-to-Digital Converter (ADC) pair 0 (AN0 and AN1). Then, the current reference of the DC/DC converter is calculated according to the lamp voltage. The controller adjusts the PWM duty cycle of the DC/DC converter to control the lamp current. Meanwhile, several fault signals are monitored by the digital signal controller. Open circuit protection and short circuit protection need rapid response, so the internal comparators (CMP1D and CMP2D) are selected to implement these two protections. At the same time, the digital signal controller measures the battery voltage through the ADC pair 1 (AN2). If the battery voltage is outside the normal operation range, the ballast will stop working. In addition, Timer2 of the DSC is used to control the operation frequency of the full-bridge inverter, and the inverter drive signal is produced through the I/O port, RB14.

Table 2 shows the dsPIC usage and Table 8 shows the block diagram of the digital signal controller.

TABLE 2: dsPIC® USAGE

Feature	Description
System clock	Internal FRC Oscillator
Input voltage protection	ADC pair 1; Timer2 for trigger
DC/DC Converter control	PWM1
Open and short circuit protection	CMP1D; CMP2D
Lamp current and voltage sample	ADC pair 0; PWM1 for trigger
Full-bridge inverter drive signal	Timer2; RB14
Fail ignition protection	Timer2
Delay function	Timer1

FIGURE 8: BLOCK DIAGRAM OF THE DIGITAL SIGNAL CONTROLLER



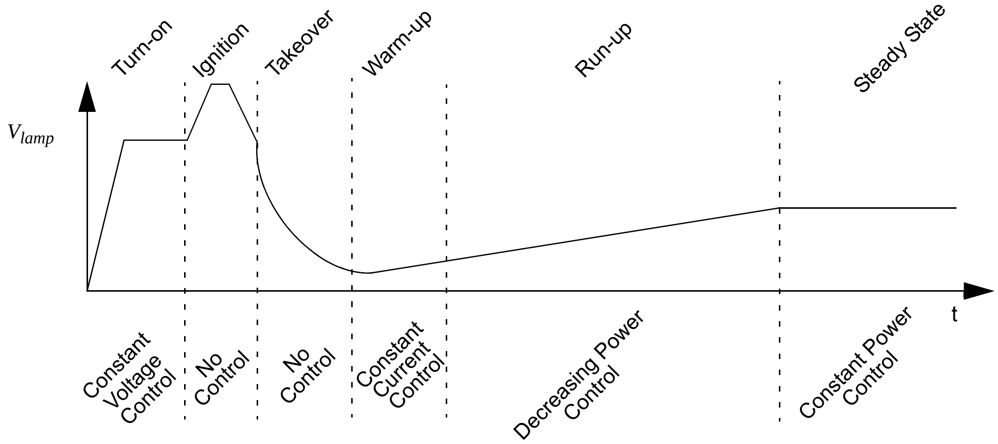
Control Strategy and Control Loop Design

CONTROL STRATEGY DESIGN

As introduced in the section **"Technical Background of Automotive HID Ballast"**, the start-up process of the automotive HID lamps consists of six stages. It needs different control strategies in every stage and the timing control is very strict. Figure 9 shows the timing flowchart of the control strategies.

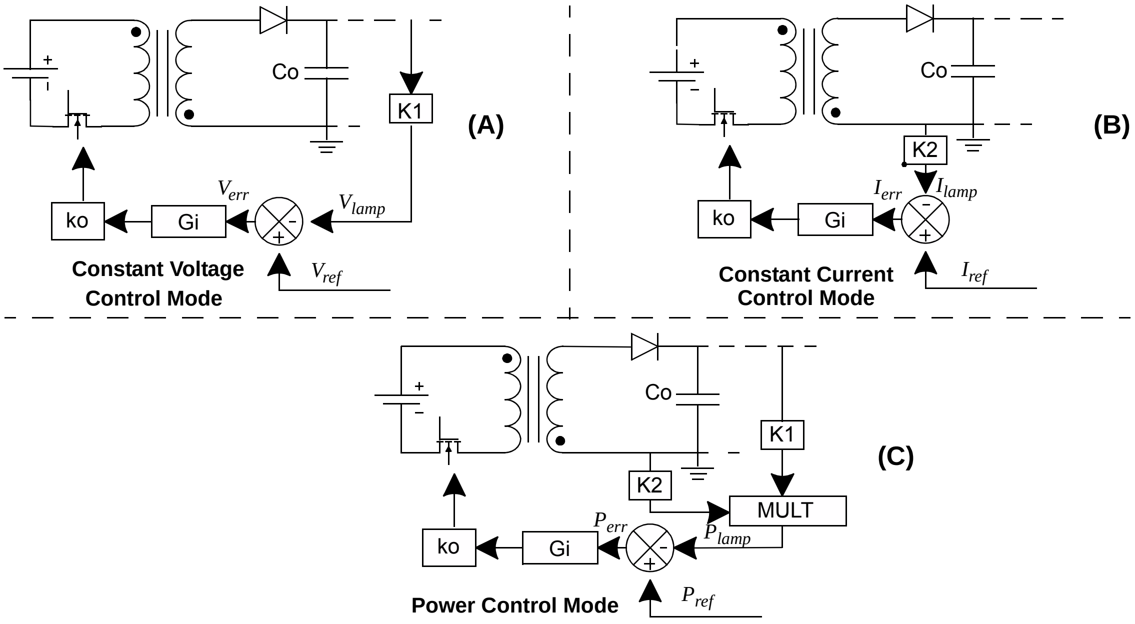
At the turn-on stage, the ballast should boost the battery voltage to a proper level. This voltage is maintained for a period of time to fully charge the igniter capacitor, until the lamp gas switches from isolation to current conductive state. The DC/DC stage works in constant voltage control in this mode, as shown in Figure 10(A). Immediately after successful ignition (lamp gas switches from isolation to current conductive state), the ballast should respond quickly and provide sufficient current to maintain the arc. Constant voltage control is replaced by constant current control at the warm-up stage, as shown in Figure 10(B). Finally, at the run-up stage and steady state, the ballast works in power control mode. When the lamp voltage exceeds 30V, it enters into the run-up stage. The ballast should control the lamp power from a high level (~75W, depending on the lamp status) to a low level (35W) until steady state. During this stage the decreasing power control mode is selected. When the lamp voltage exceeds 65V, the lamp enters into a steady state. The ballast operates at constant power control to maintain the lamp power at 35W, ±1W. The steady state schematic is illustrated in Figure 10(C).

FIGURE 9: TIMING FLOWCHART OF THE CONTROL STRATEGIES



Note: This figure shows the "as is" magnitude profile of the lamp. Its direction is not illustrated here.

FIGURE 10: VOLTAGE, CURRENT AND POWER CONTROL DIAGRAMS (A, B, AND C)



Three different control modes (voltage, current, and power) are needed during the start-up process, which makes the software quite complex. However, the features of the dsPIC DSC minimize the complexity of the software design. For example:

- Interrupt driven control with multiple priorities
- Intelligent peripherals to minimize software overhead
- High performance math and DSP engine to efficiently perform complex calculations
- Built-in comparators to provide high-speed, reliable protection
- Simultaneous sampling ADC for accurate power measurements

In addition, there are two transitions between two control mode changes in the process. The first transition is between the voltage control mode and current control mode. This may delay the current response of the DC/DC converter after ignition, which may lead to the lamp arc becoming extinguished. The second transition is between the current control mode and power control mode, which will lead to instability of the lamp current. Considering this, the control mode is optimized in this reference design. Only current control mode is employed for the entire start-up process. An advanced scheme is implemented using the dsPIC DSC, which achieves the various control modes without the drawbacks of unstable lamp current or extinguishing of the ignition arc.

First, the constant voltage control mode in the turn-on stage is replaced by the constant current control mode. The maximum output voltage of the DC/DC converter is limited by the cycle-by-cycle Current-Limit function of the digital signal controller's PWM module. The limited voltage value should be set for the ignition circuit (somewhere between 360V to 400V for igniter circuitry components tolerance). This accelerates the current response of the DC/DC converter, and contributes to a high ignition success rate. Also, the takeover current supplied by the auxiliary current circuit is reduced; therefore, the auxiliary current capacitor can be a smaller one.

Next, the power control mode is replaced by the current control mode in the run-up stage and steady state. When the start-up process enters into the run-up stage from the warm-up stage, there is no control mode transition, which may lead to instability of the lamp current. In this way, we can control the lamp current to achieve lamp power control. The current reference in these two stages is calculated, as shown in Equation 3.

EQUATION 3: CURRENT REFERENCE FORMULA

$$I_{ref} = \frac{P_{ref}}{V_{lamp}}$$

Where:

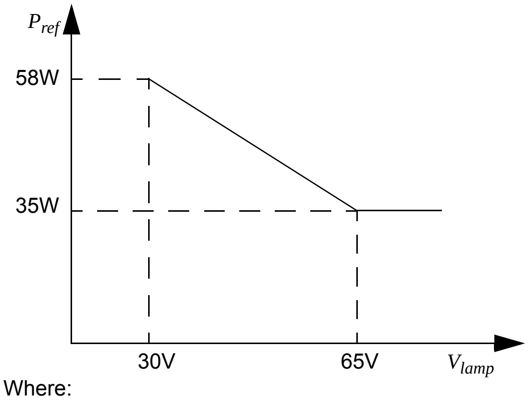
I_{ref} is the lamp current reference

P_{ref} is the lamp power reference

V_{lamp} is the lamp voltage

During these two stages (Run-up and Steady), the power reference is determined by lamp voltage sampled by the digital signal controller's ADC module. The relationship between the power reference and lamp voltage is shown in Figure 11.

FIGURE 11: POWER REFERENCE AND LAMP VOLTAGE



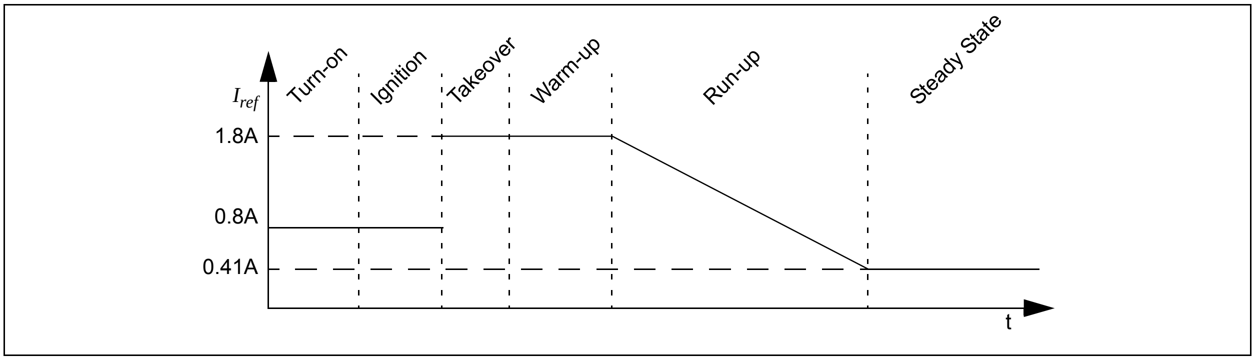
Where:

P_{ref} is the lamp power reference

V_{lamp} is the lamp voltage

As discussed previously, the current reference of the regulator during the entire start-up process is shown in Figure 12.

FIGURE 12: CURRENT REFERENCE



CURRENT CONTROL LOOP DESIGN

The full-bridge inverter converts the DC voltage into low-frequency square wave AC in a fully symmetrical pattern. Therefore, the small signal modeling of the ballast will only be conducted on the flyback converter. As introduced in the section **"Control Strategy and Control Loop Design"**, there is only a current loop in this reference design. Figure 13 shows the block diagram of the current loop.

Table 3 lists the design parameters of the current loop at steady state.

TABLE 3: CURRENT LOOP DESIGN PARAMETERS

Design Parameter	Value
Output Power	P_o = 35W
Output Current	I_o = 0.41A
Input Voltage	V_i = 13.5V
Operation Frequency	f_s = 180 kHz
Current Loop Sampling Frequency	f = 22.5 kHz
Primary Inductance	L_p = 3.47 µH
Duty Cycle	D = 0.51
Turn Ratio	n = 6
Current Loop Bandwidth	f_{sw} = 200 Hz

EQUATION 4: ORIGINAL TRANSFER FUNCTION

$$G(s) = G_m(s) \cdot G_p(s) \cdot H(s)$$

Where:

$G_m(s)$ is PWM generator function

$G_p(s)$ is the power stage function

$H(s)$ is the feedback function

The PWM generator function $G_m(s)$ = 1/8. The feedback function consists of two parts, one is the sample resistance (0.68Ω) and the other is the proportional amplifier (gain is 2). Therefore, the value of $H(s)$ is 1.36. The power stage function, $G_p(s)$, is calculated by the flyback small signal module as shown in Figure 14.

FIGURE 13: CURRENT LOOP BLOCK DIAGRAM

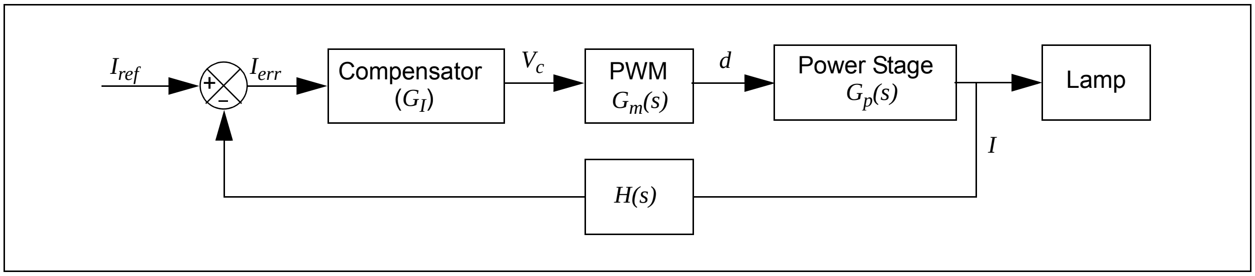
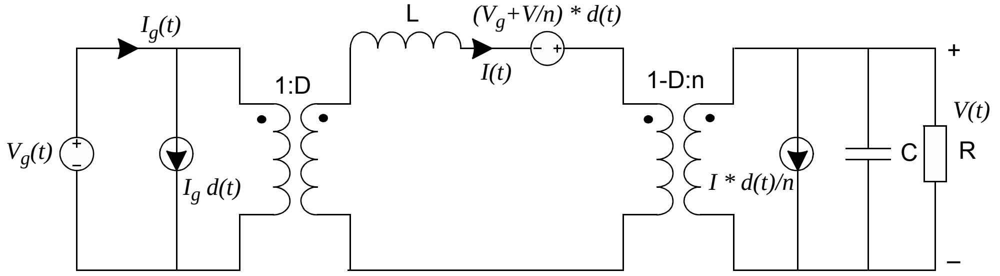


FIGURE 14: SMALL SIGNAL MODEL OF THE FLYBACK CONVERTER



Based on Figure 14, the power stage function, $G_p(s)$, is calculated in Equation 5. As a result, the entire original transfer function is calculated, as shown in Equation 6.

EQUATION 5: POWER STAGE TRANSFER FUNCTION

$$G_p(s) = \left.\frac{v(t)}{R\cdot dt}\right|_{V_g(t)=0} = \frac{V_o}{R}\cdot\frac{\frac{D'}{D}-\frac{L_p}{D'\cdot R}s}{n^2L_pCs^2+\frac{n^2L_p}{R}s+D'^2}$$

Where:

V_o = the input voltage

D = the duty cycle

D' = (1-D)

R = the lamp equivalent resistance

L_p = the primary inductance

EQUATION 6: ENTIRE ORIGINAL TRANSFER FUNCTION

$$G(s) = G_m(s)\cdot G_p(s)\cdot H(s) = \frac{V_o}{R}\cdot\frac{\frac{D'}{D}-\frac{L_p}{D'\cdot R}s}{n^2L_pCs^2+\frac{n^2L_p}{R}s+D'^2}\cdot\frac{1.36}{8}$$

Where:

$G_m(s)$ = PWM module transfer function

$H(s)$ = Feedback circuitry transfer function

EQUATION 7: CURRENT ERROR COMPENSATOR

The transfer function for the current error compensator is given by:

$$G_I(s) = k_{pi}+\frac{k_{Ii}}{s} = k_{pi}\left(\frac{1+T_{co}\cdot s}{T_{co}\cdot s}\right)$$

Where f_z = 20 Hz, which is the location of zero for the current PI controller and,

$$T_{co} = \frac{1}{2\pi f_z} = 0.00796$$

$$G_I(s) = \frac{nL_pCD'^2R^2f_{sw}}{V_oL_p}\cdot\frac{8}{1.36}\cdot\left(\frac{1+T_{co}\cdot s}{T_{co}\cdot s}\right)$$

$$\Rightarrow G_I(s) = 0.1162\cdot\left(\frac{1+0.00796\cdot s}{0.00796\cdot s}\right)$$

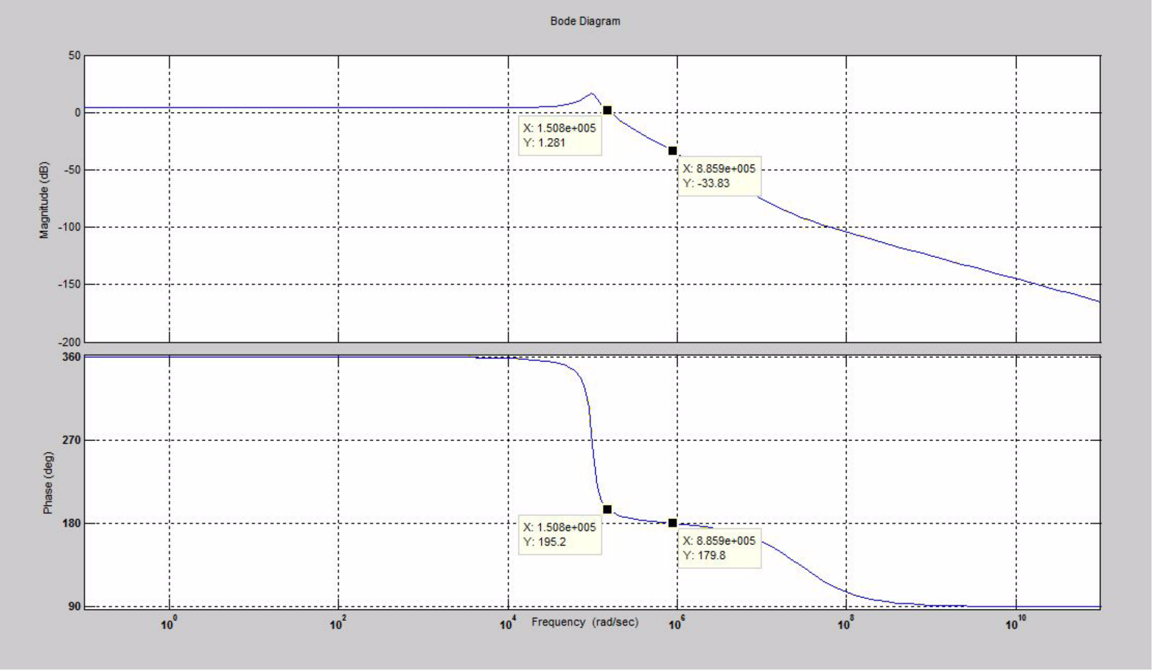
$$\Rightarrow G_I(s) = 0.1162+\frac{14.59}{s}$$

Based on Equation 7,

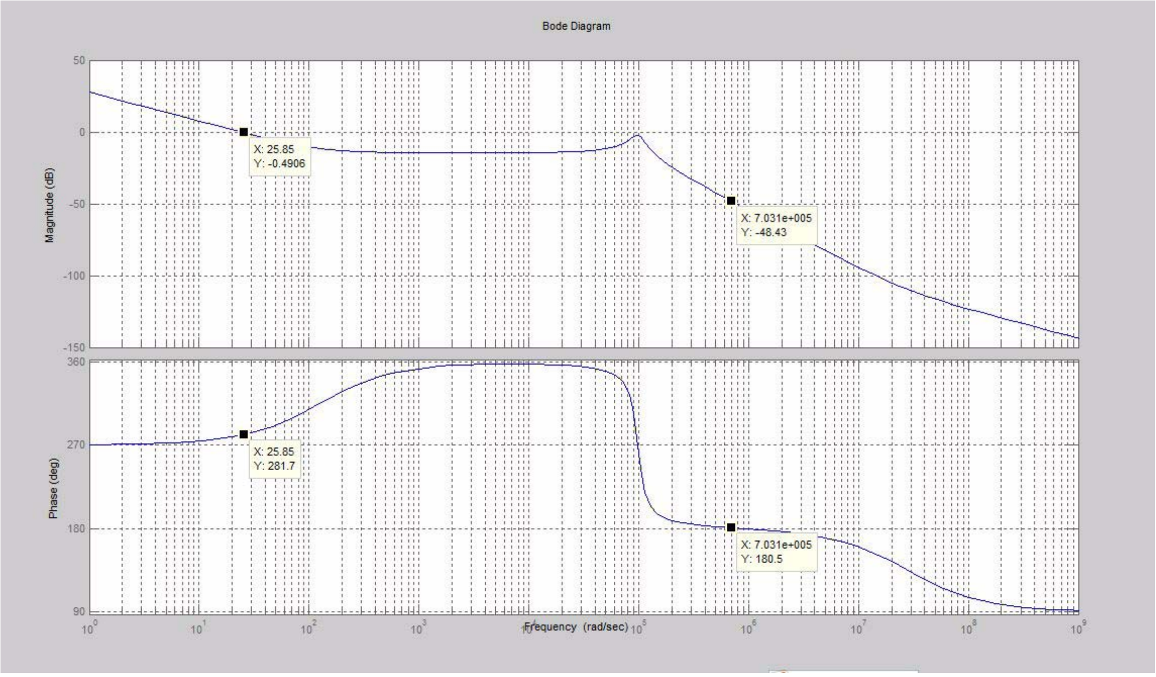
k_{pi} = 0.1162 and k_{Ii} = 14.59/Sampling Frequency = 0.00065.

Figure 15 shows bode plots of the original transfer function and compensated transfer function.

FIGURE 15: ORIGINAL AND COMPENSATED BODE PLOTS



Original Functions (Gain Margin 33.83 dB, Phase Margin 15.2º)

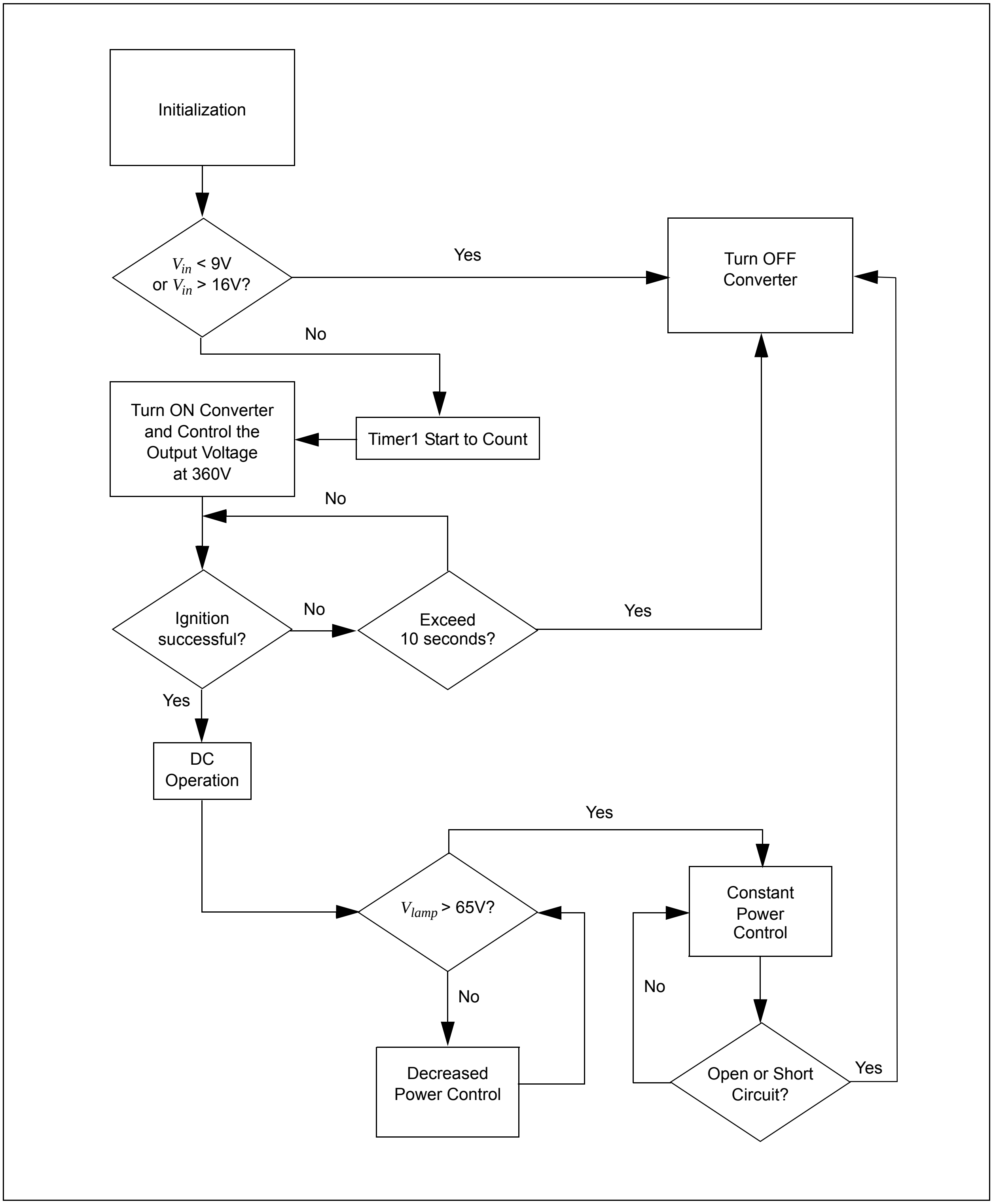


Compensated Functions (Gain Margin 48.43dB, Phase Margin 101.7°)

SOFTWARE DESIGN

Figure 16 shows the control flowchart of the system.

FIGURE 16: CONTROL FLOWCHART



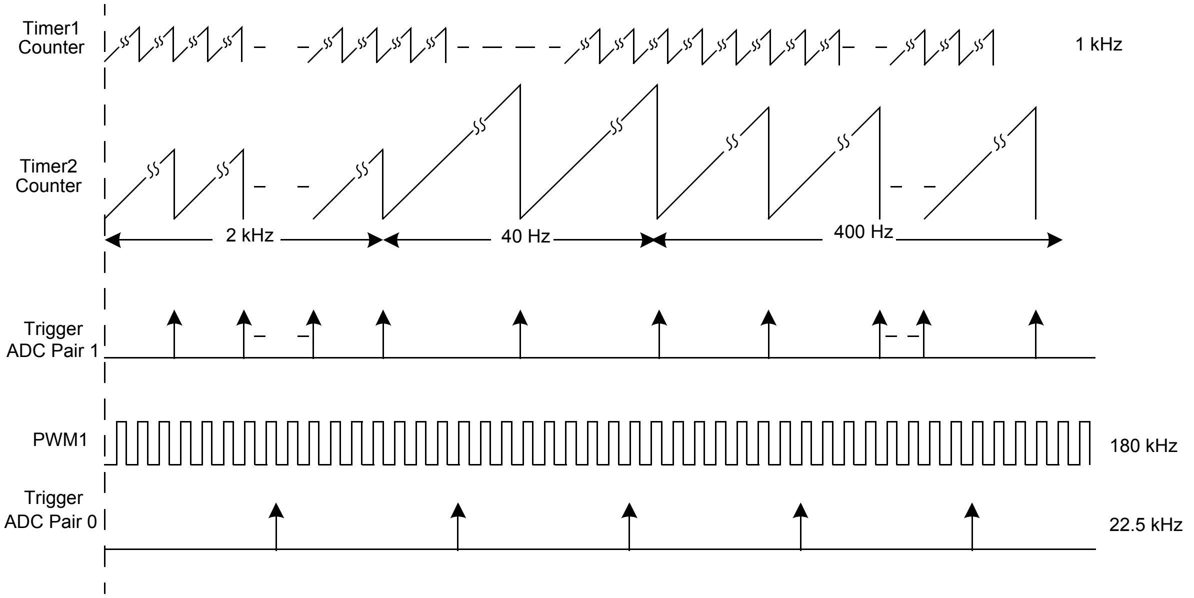
Timing Logic for Software Implementation

Timer1 runs at a frequency of 1 kHz. It is the time base for the delay subroutine function, which is used in the ignition failure detection. Timer2 is used for the full-bridge inverter drive signal and runs at a different frequency.

Before ignition, Timer2 runs at a frequency of 2 kHz to charge the igniter capacitor. After ignition, Timer2 runs at 40 Hz to warm-up the lamp electrode. After the warm-up stage, Timer2 runs at 400 Hz and remains at this frequency. In addition, Timer2 triggers ADC pair 1 every period to sample the battery voltage.

PWM1 runs at 180 kHz. It also triggers ADC pair 0 every eight cycles. Lamp voltage and lamp current are sampled by ADC pair 0. An ADC interrupt is served on every trigger. In the Interrupt Service Routine (ISR), the digital signal controller reads the ADC result, checks the lamp status, executes the compensator, and then updates the PWM duty cycle to deliver proper power to the lamp. The timing diagram is illustrated in Figure 17.

FIGURE 17: TIMING LOGIC



Software Flow

The software flow is shown in Figure 18.

At power-up, all of the variables and peripherals are initialized. PWM1 is configured to run at 180 kHz. Timer1 and Timer2 are configured to 1 kHz and 2 kHz separately. On every period, Timer2 generates an interrupt. Output pin RB14 is toggled in the interrupt service routine to provide the PWM for the Full-Bridge MOSFETs. Ignition time-out and warm-up completion detection is also implemented in this interrupt service routine. ADC pair 1 is also triggered by Timer2. However, its result is read and checked in background to detect whether the battery voltage is in the expected range.

On every eighth PWM cycle, PWM1 triggers ADC pair 0 to sample the lamp current and voltage, and most of the control algorithm is implemented in the ADC pair 0 interrupt service routine. An ignition success flag is checked at the entrance of the interrupt service routine.

If the ignition flag = 0, the program flows into the ignition check function. If the ignition is detected, the ignition flag is set. The Timer2 period is reconfigured to 40 Hz for warm-up operation. Then, the program flows into the warm-up function. If the ignition is not detected, the program jumps to the open loop control flow.

If the ignition flag = 1, warm-up code is executed. After the warm-up stage the lamp voltage is checked. If the lamp voltage is larger than 65V, the program jumps to the constant power control flow. A fixed power reference (35W) is divided by lamp voltage. The result is fed to the current compensator as the current reference. If the lamp voltage is smaller than 65V, the program flows to decreased power control flow. A variable power reference, as illustrated in Figure 11, is divided by the lamp voltage. The result is feed to the current compensator as the current reference. The compensator is then executed, and feeds its result to the PWM module.

FIGURE 18: SOFTWARE FLOW

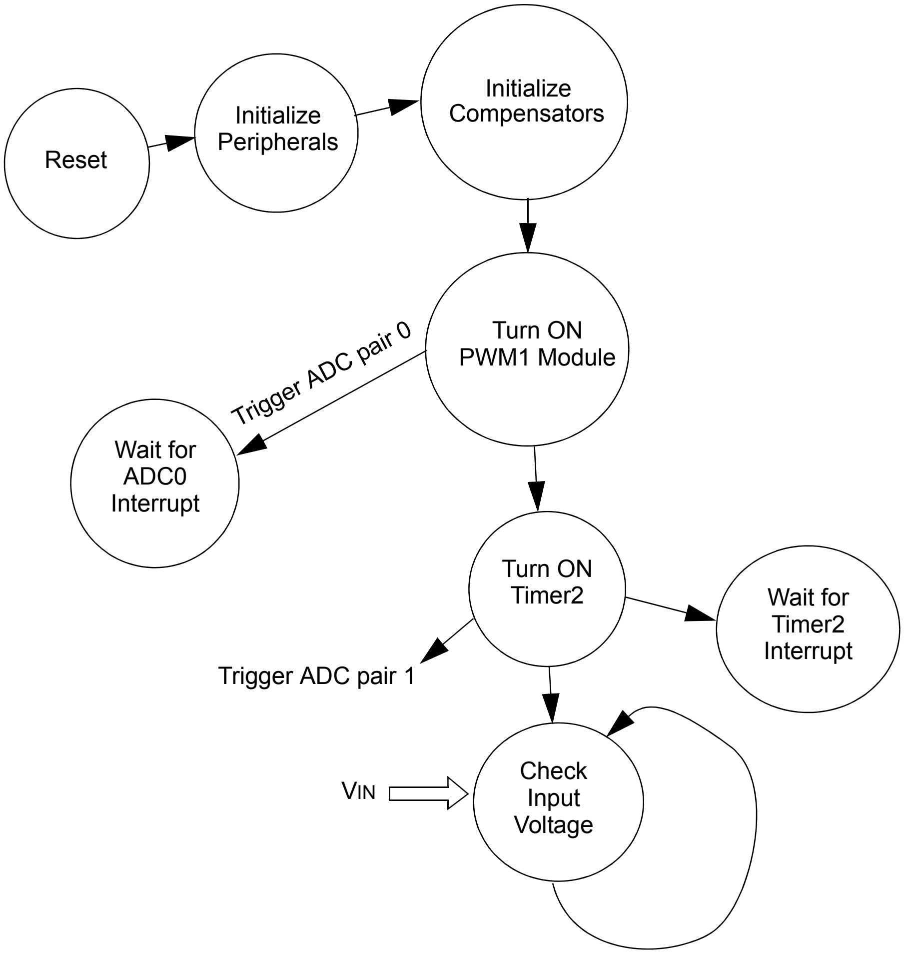


FIGURE 19: TIMER2 INTERRUPT SERVICE ROUTINE (ISR) FLOW

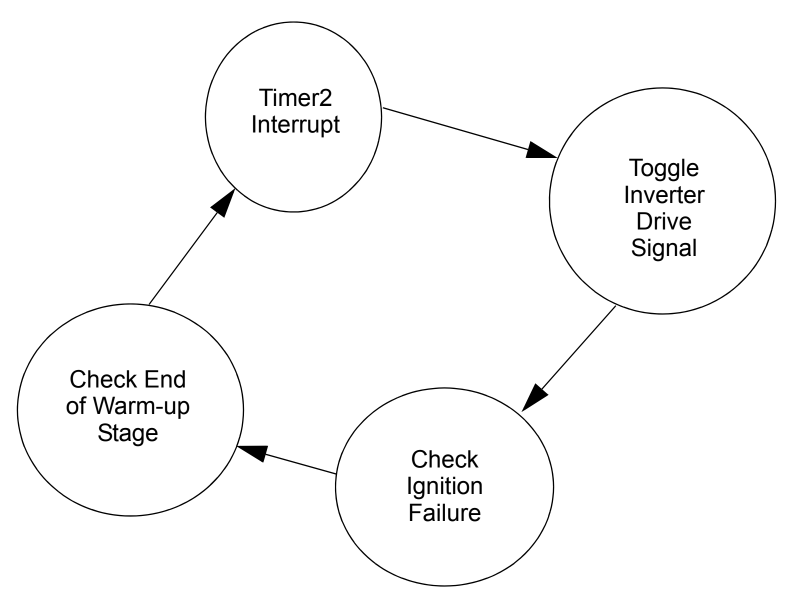
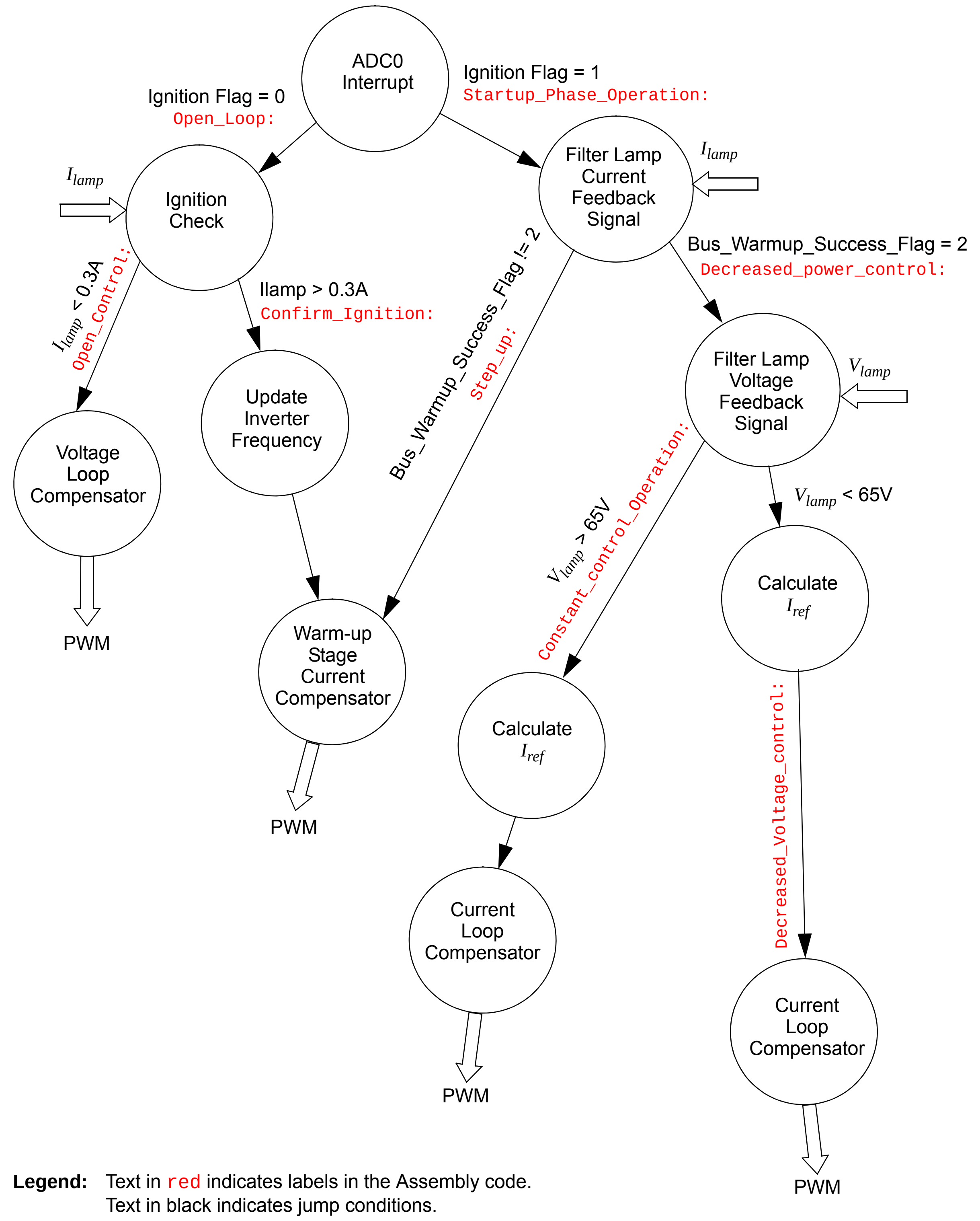


FIGURE 20: ADC INTERRUPT SERVICE ROUTINE (ISR) FLOW



Legend: Text in red indicates labels in the Assembly code.
Text in black indicates jump conditions.

Functions Used in Software

The functions listed in Table 4 and Table 5 are used in software for implementing the various stages of the automotive HID lamp ballast.

TABLE 4: SOFTWARE FUNCTION

File Name	Function Name	Description
`main.c`	`main()`	Digital signal controller frequency configuration.
		Auxiliary clock configuration.
		PWM, CMP, and ADC configuration.
		Compensator initialization.
		Enable the PWM and ADC.
		Enable the full-bridge drive.
		Check the input voltage fault.
`init.c`	`init_FlybackDrive()`	PWM1 module configuration.
	`init_CMP()`	CMP1D and CMP2D configuration.
	`init_ADC()`	ADC pair 0 and ADC pair 1 configuration.
	`init_FlybackCurrentCtrl()`	Initialize flyback compensator.
	`Delay_ms`	Time delay configuration.
	`init_Timer2_full_bridge_drive()`	Full-bridge inverter drive signal configuration.
	`Init_Variables()`	Reset variables and flags.
	`Init_IO()`	Initialize RB14 as output for full-bridge PWM signal.
`isr.c`	`T1Interrupt()`	Increment interrupt counter.
	`T2Interrupt()`	Toggle I/O.
		Ignition time-out check.
		End of warm-up check.
	`FlybackCurrentCntrl()`	Flyback compensator.
`isr_asm.s`	Refer to Table 5.	

TABLE 5: `isr_asm.s` FUNCTION

File Name	Section Label	Description
`isr_asm.s`	`Startup_Phase_Operation`	Filter lamp current.
	`step_up`	Warm-up current control.
	`Decreased_power_control`	Filter lamp voltage.
		Provide current reference by lamp voltage condition.
	`Decreased_current_control`	Run-up stage current loop control.
	`Power_Control_Operation`	Current reference calculation.
		Power loop control.
	`Open_Loop`	Ignition success check.
	`Open_control`	Open voltage control.
	`Confirm_ignition`	Set ignition success flag.
		Configures DC operation frequency.
		Filters initialization.

HARDWARE DESIGN

System Block Diagram

Figure 21 shows the system circuit diagram of the reference design. As introduced in the section **"Hardware Topology Selection"**, the design consists of four major sections. In addition, the design also includes several auxiliary circuits.

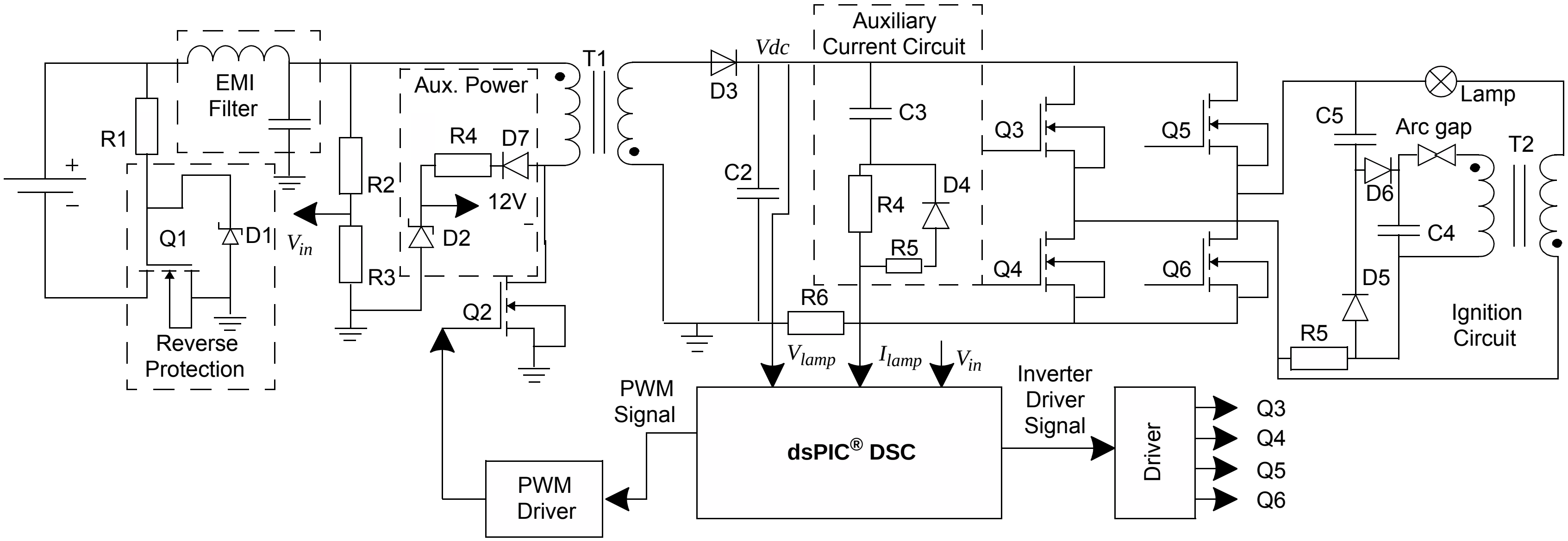
An EMI filter at the input side attenuates the Electromagnetic Interference (EMI). At the same time, a reverse input-voltage protection circuit is also at the input side. Moreover, an RCD auxiliary current circuit before the full-bridge inverter provides the major take-over current before the response of the converter. A signal filter adjusts the lamp voltage and current signals before the ADC. Finally, the auxiliary power system supplies the digital and analog ICs on the board.

Power Stage Parameter Design

TABLE 6: FLYBACK DESIGN DATA

Design Parameter	Value
Rated input voltage	V_{in} = 13.5V
Minimum input voltage	V_{in_min} = 9V
Maximum input voltage	V_{in_max} = 16V
Rated output voltage	V_o = 85V
Minimum output voltage	V_{o_min} = 30V
Maximum output voltage	V_{o_max} = 102V
Rated output current	I_o = 0.41A
Maximum output current	I_{o_max} = 1.8A
Rated output power	P_o = 35W
Maximum output power	P_{o_max} = 75W
Operation frequency	f_s = 180 kHz
System efficiency	η= 85%
Diode forward voltage	V_f = 1V

FIGURE 21: SYSTEM CIRCUIT DIAGRAM



Note: In this design, the input inrush current at the start of ignition is not controlled. To reduce this inrush current, it is recommended to use the internal comparator of the dsPIC device. The comparator should be set as the trigger source of the PWM Current-Limit mode.

CALCULATION OF THE TRANSFORMER TURNS RATIO n

EQUATION 8: MAXIMUM DRAIN-TO-SOURCE VOLTAGE $Vds\_\max$ OF MOSFET

$$V_{ds\_\max} = V_{in\_\max} + \frac{V_{ig}}{n} + V'$$

Where:

Output voltage for ignition circuit: V_{ig} = 360V

Max input voltage: $V_{in\_\max}$ = 16V

Overshoot voltage: $V' \approx$ 15V

Max drain-to-source voltage of MOSFET: V_{DSS} = 100V

Max drain-to-source voltage: $V_{ds\_\max}$ = 90% * V_{DSS} = 90V

Based on Equation 8, the transformer turns ratio is n = 6.

CALCULATION OF THE PRIMARY INDUCTOR L_p

EQUATION 9: VOLTAGE RATIO V_{in}/V_o OF THE CONVERTER AT RATED OPERATION

$$V_o = \frac{n \cdot V_{in} \cdot D}{1 - D}$$

Where:

Rated input voltage: V_{in} = 13.5V

Rated output voltage: V_o = 85V

Duty cycle: D

Calculated turns ratio: n = 6

Based on Equation 9, the duty cycle at rated operation D = 0.51.

The flyback converter works at CCM mode at rated operation.

EQUATION 10: CURRENT PARAMETERS OF THE PRIMARY INDUCTOR

According to the power conservation, the average input current is:

$$I_{in\_ave} = \frac{P_o}{V_{in} \cdot \eta}$$

Where:

Rated output power: P_o = 35W

Rated input voltage: V_{in} =13.5V

System efficiency: η= 85%

The average current during the on period is:

$$I_{ave\_on} = \frac{I_{in\_ave}}{D}$$

Where:

Duty cycle: D = 0.51

The peak current of the primary inductor is:

$$I_{L\_pk} = I_{ave\_on} + \frac{\Delta I}{2}$$

Where:

Assumed inductor ripple current: ΔI = 11A

The RMS current of the primary inductor is:

$$I_{L\_rms} = I_{L\_pk} \cdot \sqrt{\frac{D}{3}}$$

Based on Equation 10, the average input current I_{in_ave} = 3.05A, the peak current of the primary inductor I_{L_pk} = 11.48A, and the RMS current of the primary inductor I_{L_rms} = 4.73A.

EQUATION 11: VALUE OF THE PRIMARY INDUCTOR

$$L_p = \frac{V_{in} \cdot t_{on}}{\Delta I}$$

Where:

Rated input voltage: V_{in} = 13.5V

Turn on time: t_{on} = D * (1/f_s) = 2.83 µs

Inductor ripple current: ΔI = 11A

Based on Equation 11, the primary inductor L_p = 3.47 µH.

SELECTION OF THE PLANAR CORE

The magnetic core cannot be saturated; therefore, the worst conditions (i.e., V_{in} = 9V; P_o = 75W; V_o = 30V) should be considered.

Based on Equation 9, the duty cycle at the worst condition D_w = 0.357.

Based on Equation 10, the average input current $I_{in\_ave\_w}$ = 9.8A, and the average on current $I_{ave\_on\_w}$ = 27.46A.

EQUATION 12: THE INDUCTOR RIPPLE CURRENT AT WORST CONDITION

$$\Delta I_w = \frac{V_{in\_\min} \cdot D_w}{f_s \cdot L_p}$$

Where:

Minimum input voltage: $V_{in\_\min}$ = 9V

Duty cycle at worst condition: D_w = 0.357

Operation frequency: f_s = 180 kHz

Primary inductor: L_p = 3.47 µH

Based on Equation 12, the inductor ripple current at the worst condition ΔI_w = 5.14A.

Based on Equation 10, the peak current of the primary inductor at the worst condition $I_{L\_pk\_w}$ = 30.03, and the RMS current of the primary inductor at the worst condition $I_{L\_rms\_w}$ = 10.36A.

The planar core is selected using the AP calculation method, as shown in Equation 13.

EQUATION 13: THE VALUE OF AP

The primary side AP is:

$$AP_p = \frac{6.33 \cdot L_p \cdot d^2{}_p \cdot 10^8}{\Delta B}(cm^4)$$

Where:

The primary inductor: L_p = 3.47 µH

The primary wire diameter: $d^2{}_p$ = 1.816 mm

Saturation magnetic induction: ΔB = 0.3T

The second side AP is:

$$AP_s \approx (2 \sim 3) \cdot AP_p$$

The entire AP is:

$$AP = AP_p + AP_s$$

Based on Equation 13, the entire AP = 0.72 cm^4.

Comparing the Magnetics planar cores, FR43208EC and FR43208IC are selected for the flyback transformer, as shown in Equation 14.

EQUATION 14: PARAMETERS OF THE SELECTED PLANAR CORES

$$AP = A_w \cdot A_e = 0.767 cm^4 > 0.72 cm^4$$

Where:

A_w = 58.99 mm^2

A_e = 130 mm^2

CALCULATION OF THE PRIMARY AND SECONDARY TURNS

EQUATION 15: THE PRIMARY AND SECONDARY TURNS

The primary turns is:

$$N_p = \frac{L_p \cdot I_{L\_pk\_w}}{\Delta B \cdot A_e}$$

Where:

The primary inductor: L_p = 3.47 µH

The peak current of the primary inductor at worst condition: $I_{L\_pk\_w}$ = 30.03A

Saturation magnetic induction: ΔB = 0.3T

A_e = 130 mm^2

The secondary turns is:

$$N_s = n \cdot N_p$$

Where:

Turns ratio: n = 6

Based on Equation 15, the primary turns N_p = 2.65, the selected N_p = 2, and the selected second turns N_s = 12.

CALCULATION OF THE TRANSFORMER GAP

EQUATION 16: TRANSFORMER GAP

$$L_{gap} = \frac{\mu_0 \cdot N_p^2 \cdot A_e}{L_p}$$

Where:

The primary turns: N_p = 2

A_e = 130 mm^2

The primary inductor: L_p = 3.47 µH

Based on Equation 16, the transformer gap L_{gap} = 0.19 mm.

POWER COMPONENTS SELECTION

- MOSFET Q1 for input voltage reverse protection

EQUATION 17: CALCULATION OF THE MAJOR MAXIMUM PARAMETERS

The maximum RMS drain current is:

$$I_{D\_rms\_\max} = I_{L\_rms\_w} = 10.36A$$

Based on Equation 17, FDD8896 is selected for Q1, V_{DSS} = 30V, R_{ds_on} = 5.7 mΩ

- MOSFET Q2 for flyback converter

EQUATION 18: CALCULATION OF THE FLYBACK MOSFET MAXIMUM PARAMETERS

The maximum drain current is:

$$I_{D\_\max} = I_{L\_rms\_w} = 10.36A$$

The maximum drain to source voltage is:

$$V_{ds\_\max} = V_{in\_\max} + \frac{V_{ig}}{n} = V' = 90V$$

Based on Equation 18, FDB3652 is selected for Q2, V_{DSS} = 100V, R_{ds_on} = 16 mΩ

- Diode D3 for flyback converter

EQUATION 19: CALCULATION OF THE FLYBACK DIODE MAXIMUM PARAMETERS

The maximum forward current is:

$$I_{F\_\max} = \frac{I_{L\_pk\_w}}{n} = 5A$$

The maximum reverse voltage is:

$$V_{R\_\max} = V_{ig} + V_{in\_\max} \cdot n = 504V$$

Based on Equation 19, RHR660 is selected for D3, V_{R_max} = 600V, $I_{F(AV)\_max}$ =6 A, Q_{rr} = 45 nC.

- MOSFET Q3-Q6 for full-bridge inverter

EQUATION 20: CALCULATION OF THE FULL-BRIDGE MOSFET MAXIMUM PARAMETERS

The maximum drain current is:

$$I_{D\_\max} = I_{o\_\max} = 1.8A$$

The maximum drain to source voltage is:

$$V_{ds\_\max} = \frac{V_{ig}}{2} = 180V$$

Based on Equation 19, FCD7N60 is selected for Q3-Q6, V_{DSS} = 650V, ID_{-rms_max} = 7A, R_{ds_on} = 0.53Ω

Ignition Circuit Parameter Design

The selected ignition circuit is driven by a dual-frequency inverter, the design parameters are shown in Table 7.

TABLE 7: IGNITION CIRCUIT DESIGN PARAMETERS

Design Parameter	Value
Rated input voltage	V_{ig} = 360V
Breakover voltage of the gas discharge tube	V_{break} = 600V
Ignition pulse voltage value	V_{ig_pulse} > 25 kV
Ignition pulse width	T_w > 0.5 µs
Inverter frequency for ignition	f_{ig} = 1 kHz

IGNITER CAPACITOR AND RESISTOR

Considering the ignition energy, the resonance capacitance C4 = 33nF/630V.

EQUATION 21: CALCULATION OF PUMP CAPACITANCE C5 AND CHARGE RESISTANCE R5

The charge and discharge time are almost the same:

$$T_{discharge} \approx T_{charge} = 5 \cdot C5 \cdot R5$$

The charge and discharge period is:

$$T_{ig} = \frac{1}{f_{ig}}$$

Where:

Inverter frequency for ignition: f_{ig} = 1 kHz

In addition, the charge time and C5 should meet:

$$T_{charge} < \frac{T_{ig}}{2} \quad \text{and} \quad C_5 \le \frac{C_4}{10}$$

Based on Equation 21, the selected pump capacitance C5 = 33nF/630V and the selected charge resistance R5 = 1k/3W.

CALCULATION OF TRANSFORMER

EQUATION 22: CALCULATION OF TURN RATIO *N*

$$n > \frac{V_{ig\_pulse}}{V_{break}}$$

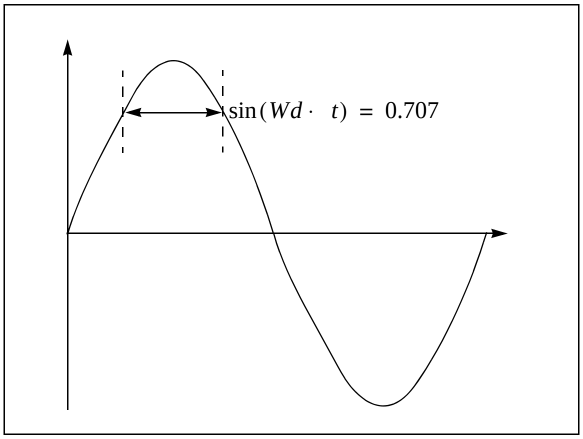
Where:

Ignition pulse voltage value: V_{ig_pulse} > 25 kV

Breakover voltage of the gas discharge tube: V_{break} = 600

Based on Equation 22, the turns ratio n > 41.7. Considering the parasitic parameters, the selected turns ratio n = 80.

FIGURE 22: RMS IGNITION PULSE WIDTH



EQUATION 23: CALCULATION OF THE PRIMARY INDUCTOR L_p

The RMS ignition pulse width is shown in Figure 22.

$$\sin(Wd \cdot t) = 0.707$$

Where:

$$Wd = \frac{1}{\sqrt{L_p \cdot C4}}$$

the resonance frequency is:

$$\Rightarrow Wd \cdot t_1 = 0.24\pi, \; Wd \cdot t_2 = 0.76\pi$$

and the ignition pulse width is:

$$T_w = t_2 - t_1 = \frac{0.76\pi - 0.24\pi}{Wd} > 0.5\mu s$$

Based on Equation 23, the primary inductor L_p > 0.28 µH, the selected L_p = 0.28 µH, and the selected L_s = 1.78 mH.

System Auxiliary Circuits Design

AUXILIARY POWER SYSTEM DESIGN

There are two auxiliary powers, one is 3.3V which supplies the digital signal controller and the op amp. The other is 15V, which supplies the full-bridge MOSFET driver. Figure 23 shows the circuit of the auxiliary power system.

The power of the 15V circuit is calculated by Equation 24.

EQUATION 24: THE POWER OF THE 15V AUXILIARY POWER CIRCUIT

$$P = \frac{1}{2} L_{p\_leak} \cdot I_{L\_pk}^2 \cdot f_s$$

Where:

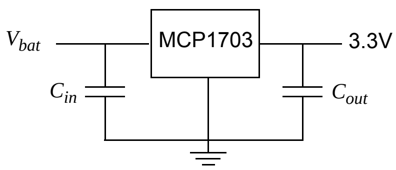
The leak inductor of the primary inductor: L_{p_leak} = 0.1 µH

The peak current of the primary inductor: I_{L_pk} = 11.48A

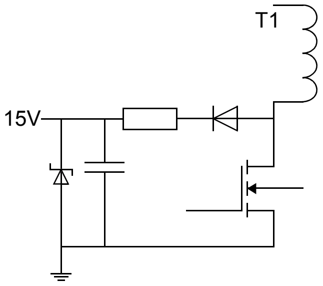
Operation frequency: f_s = 180 kHz

Based on Equation 24, the power of the 15V auxiliary power, P = 1.18W.

FIGURE 23: AUXILIARY POWER SYSTEM CIRCUITS



3.3V Auxiliary Power Circuit



15V Auxiliary Power Circuit

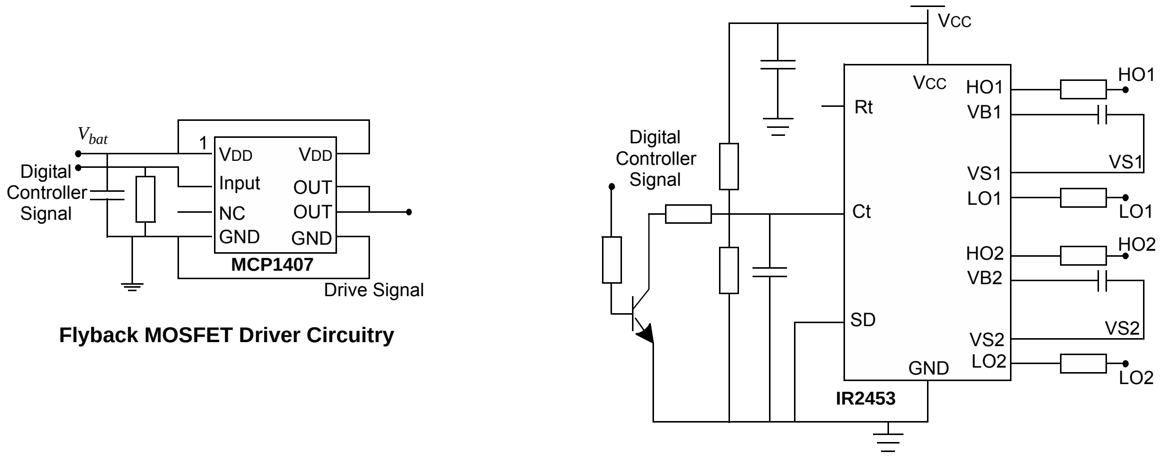
MOSFET DRIVER DESIGN

There are five drive signals in the design, one is the flyback MOSFET drive signal and the other four are the full-bridge inverter MOSFETs. A MCP1407 IC is used to drive the flyback MOSFET. A IR2453 IC is used to drive the four full-bridge MOSFETs. The dead time is fixed at 1 µs. Figure 24 shows the two drive circuits.

SIGNAL FILTER DESIGN

An op amp is used the amplify and filter the lamp voltage and current feedback signals. Figure 25 shows the two signal filters. Equation 25 calculates the transfer function of the two filters.

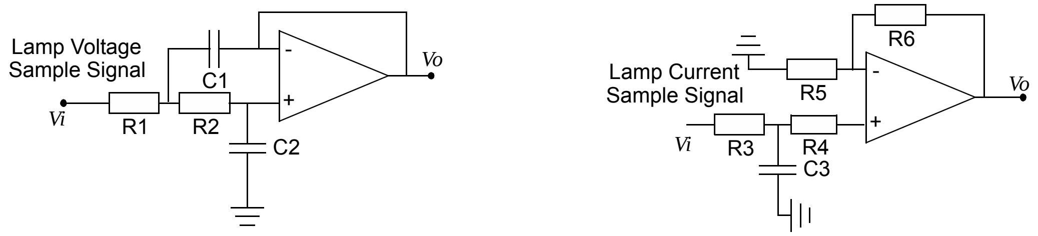
FIGURE 24: MOSFET DRIVER CIRCUITS



Flyback MOSFET Driver Circuitry

Full-bridge MOSFETs Driver Circuitry

FIGURE 25: SIGNAL FILTER CIRCUITS



Lamp Voltage Feedback

Lamp Current Feedback

EQUATION 25: THE TRANSFER FUNCTION OF THE TWO FILTERS

The voltage filter transfer function is:

$$\frac{V_o}{V_i} = \frac{1}{C_1C_2R_1R_2 \cdot \ s^2 + (C_2R_1 + C_2R_2) \cdot \ s + 1}$$

The current filter transfer function is:

$$\frac{V_o}{V_i} = \frac{R_5 + R_6}{R_5} \cdot \frac{1}{C_3R_3 \cdot \ s + 1}$$

GETTING STARTED

Figure 26 shows an overhead view of the demonstration panel. Inside the demonstration case, there is a 12 VDC/6.5 AH gel cell battery as well as a battery charger, which enables stand-alone operation. The HID lamp and the ring-type fluorescent lamp are connected to the battery independently and have their own ON/OFF switches.

1. Xenon HID lamp with fixture.
2. Ring-type fluorescent lamp.
3. Igniter.
4. Power socket for battery charger.
5. dsPIC33FJ06GS202 Digital Ballast Board:

   A green LED on the Ballast Board, when lit, indicates that the 3.3V control circuitry power is available.

   A red LED on the Ballast Board, when lit, indicates that the battery voltage is too low to support board operation. When this occurs, set both of the ON/OFF switches to the OFF position and connect a power cord to the battery charger socket.

   The dsPIC33FJ06GS202 Digital Ballast Board does not control either the ring-type fluorescent lamp or the Hi/Lo beam function.
6. HID lamp ON/OFF switch.
7. Ring-type fluorescent lamp ON/OFF switch.
8. Hi/Lo beam switch.

Application Code Programming

The MPLAB® ICD 2, MPLAB IDC 3, PICkit™ 3, and MPLAB REAL ICE™ in-circuit emulators may be used along with MPLAB IDE to debug and program your software. MPLAB IDE is available for download from the Microchip web site.

Special software interacts with the MPLAB IDE application to run, stop, and single-step through programs. Breakpoints can be set and the processor can be reset. Once the processor is stopped, the register's contents can be examined and modified. For more information on how to use MPLAB IDE, refer to the following documentation:

- *"MPLAB® IDE User's Guide"* (DS51519)
- *"MPLAB® IDE Quick Start Guide"* (DS51281)
- MPLAB® IDE Help

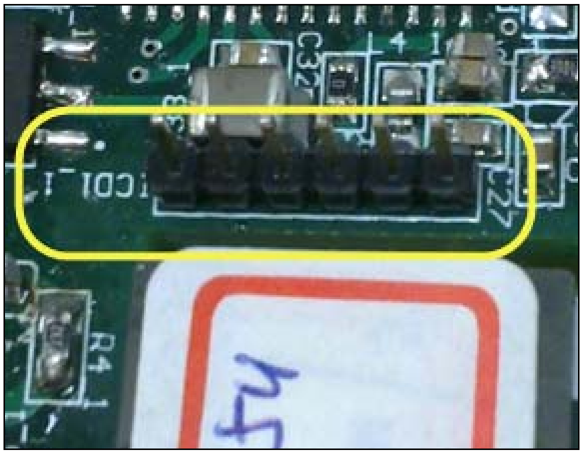
FIGURE 26: DEMONSTRATION PANEL AND COMPONENTS

Programming the Application

Complete the following steps to program the demonstration board:

1. Make sure that the ON/OFF switch for the HID lamp is in the OFF position.
2. Connect the emulator header to the 6-pin connector labeled ICD_1.

FIGURE 27: EMULATOR CONNECTOR POSITION



3. Set the ON/OFF switch for the HID lamp to the ON position.
4. Start MPLAB IDE and open the HID Ballast demonstration project by double-clicking the `.mcw` file. The remaining steps take place within MPLAB IDE.
5. Build the project by selecting *Project > Build All*.
6. Choose the desired programmer, such as MPLAB ICD 3, by selecting *Programmer > Select Programmer*.
7. Program the device by selecting *Programmer > Program*.
8. After the device has been programmed, set the ON/OFF switch for the HID lamp to the OFF position.
9. Disconnect the emulator header from the 6-pin connector labeled ICD1_1.

The HID Ballast board is now programmed and ready to run the demonstration.

> **Note:** When debugging the HID Ballast with the emulator, the connection between the PC and the board can be lost due to noise interference from lamp ignition. Therefore, it is recommended to use Programming mode.

Running the Application Demonstrations

This section describes three different automotive headlight demonstrations:

- HID lamp operation with full digital control
- Ring-type fluorescent lamp operation
- Hi/Lo-beam operation

All three of these demonstrations can be run either simultaneously or separately using the following steps (refer to Figure 26 for switch locations):

1. To operate the HID lamp, use the lamp's ON/OFF switch.

   When the lamp is switched ON, a high-pitched buzzing noise may be present at the start of ballast operation. This is normal and is not a cause for concern.
2. To check hot lamp operation, do the following:
   a) Run the lamp for at least one minute to bring the lamp to a high temperature.
   b) After one minute, turn the HID lamp OFF by setting the lamp's ON/OFF switch to the OFF position.
   c) Wait for a few seconds and then set the lamp's ON/OFF switch to the ON position. The lamp should light immediately.
3. To check cool lamp operation, do the following:
   a) Make sure the HID lamp is cold. The lamp should be switched to the OFF position for at least 10 minutes.
   b) Set the lamp's ON/OFF switch to the ON position. The lamp should light immediately.
4. To run the ring-type fluorescent lamp demonstration, simply toggle the lamp's ON/OFF switch.
5. To run the Hi/Lo-beam demonstration, simply toggle the Hi/Lo-beam ON/OFF switch.

> **Warning:** When the lamp is lit, the light emitted is very strong, which may cause physical harm to your eyes.
>
> In addition, the lamp tube may rise to a very high temperature in just a few seconds. Do not touch the lamp or allow any flammable objects to come in contact with the lamp tube.
>
> **FAILURE TO HEED THESE WARNINGS COULD RESULT IN PROPERTY DAMAGE OR BODILY HARM.**

LABORATORY TEST RESULTS AND WAVEFORMS

The final prototype of the automotive HID ballast was tested according to the technical requirements. The test results are shown in Table 8. The testing conditions are as follows:

- Test lamp: Xenon HID lamp, 35W, color temperature 6000K.
- Ambient temperature: 25ºC, ±5ºC
- Test input voltage: 9V-16V
- Rated voltage: 13.5V
- Oscilloscopes: YOKOGAWA DLM2024
- Voltage source: Chroma 62024P-80-60

Figure 28 through Figure 37 show the various waveforms including lamp current, voltage and power from the turn-on stage to the steady state, and provides a magnified view in every stage. In addition, the ignition curve and the input current curve are shown to verify the reference design.

TABLE 8: TEST RESULTS

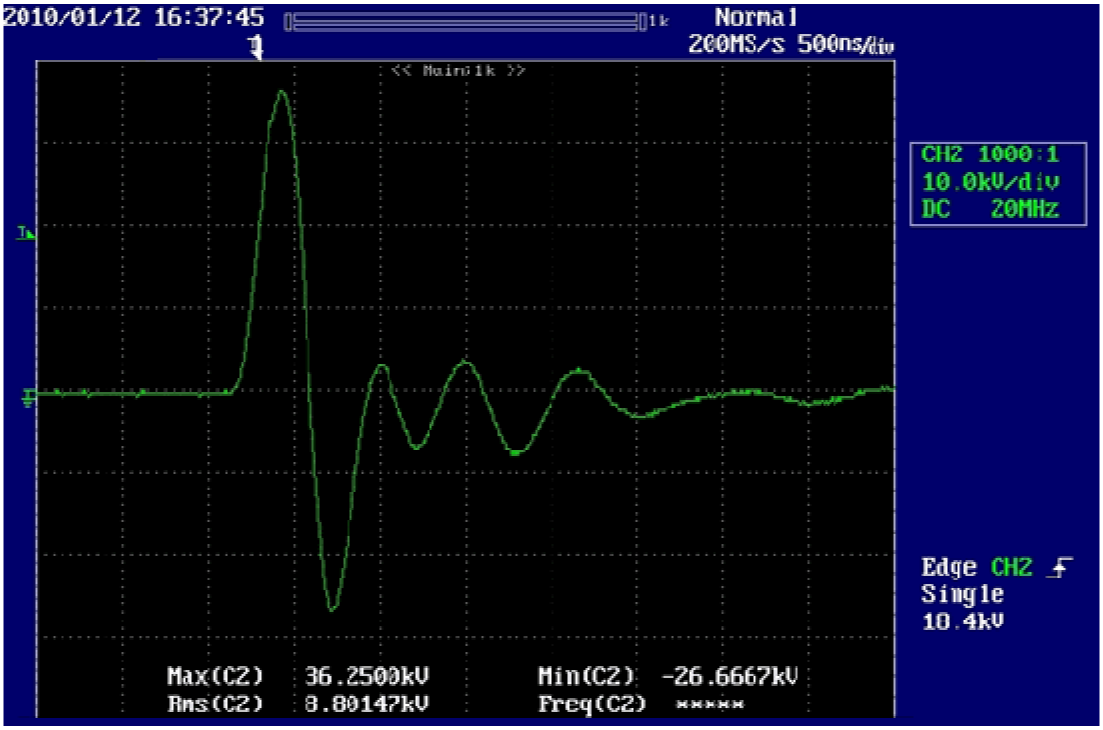
Characteristic		Test Result	Comments
Input Voltage	Nominal (13.5V)	Passed	—
	Operation (9V-16V)	Passed	—
Temperature	Operation (-40ºC to 105ºC)	Passed	—
Transient	Maximum Output Current	1.8A	VIN = 9.4V-16V
	Maximum Input Power	101W	VIN = 9.4V
	Maximum Output Power	82.5W	VIN = 13.5V
		78W	VIN = 16V
		83.5W	VIN = 9.4V
	Light Output	70.2W	VIN = 13.5V
		67.2W	VIN = 16V
	Input Current	3A	VIN = 13.5V
Steady	Output Power	35W	VIN = 13.5V
	Time to reach steady light output	Passed	≤150s
	Efficiency	85.91%	VIN = 13.5V
	Acoustic Resonance	No	—
Flicker	Restrike	100%	—
Reliability	Successive Operating	Passed	—
	Undervoltage Protection	9.4V	—
Input Protection	Overvoltage Protection	16V	—
	Short Circuit Protection	3A	—
Output Protection	Open Circuit Protection	360V	—

Table 9 summarizes the resources required by the HID Ballast design in terms of memory size, peripherals, MIPs, etc.

TABLE 9: dsPIC RESOURCE USAGE

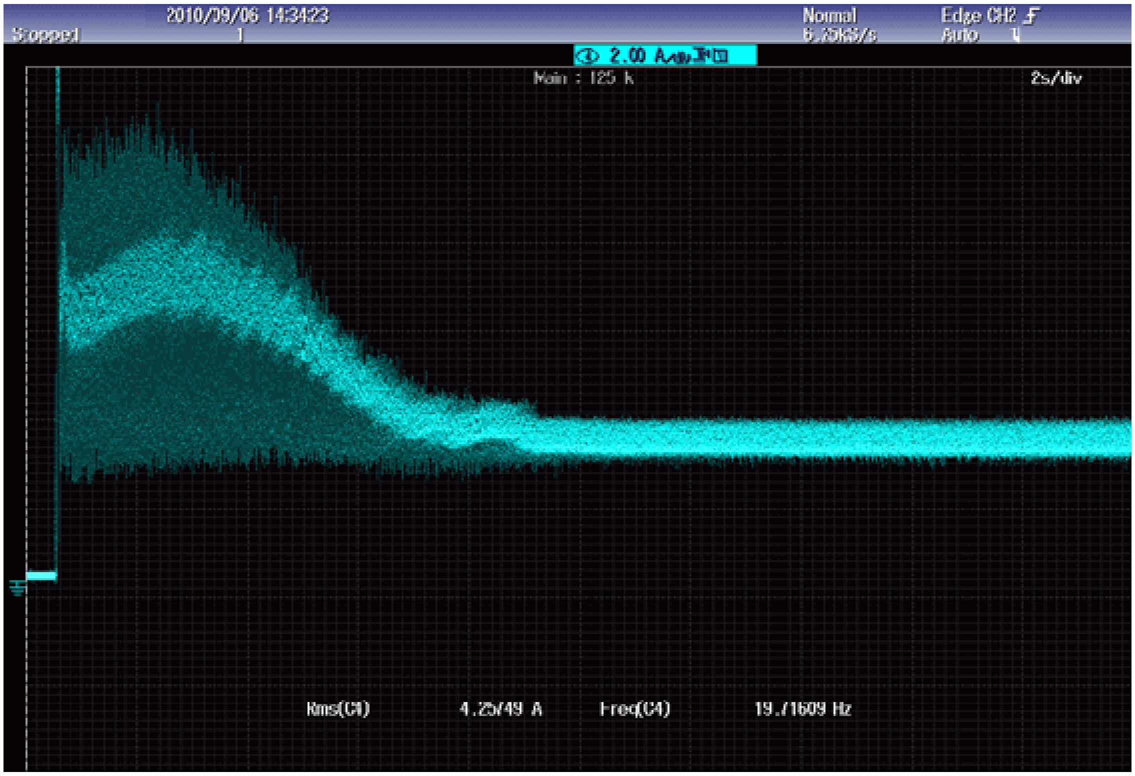
Resource	Value
Program Memory	2048 bytes
Data Memory	1024 bytes
PWM	1 channel
ADC	3 channels
Comparator	2 channels
MIPs	3.5
I/O	1 channel

FIGURE 28: IGNITOR OUTPUT VOLTAGE WAVEFORM



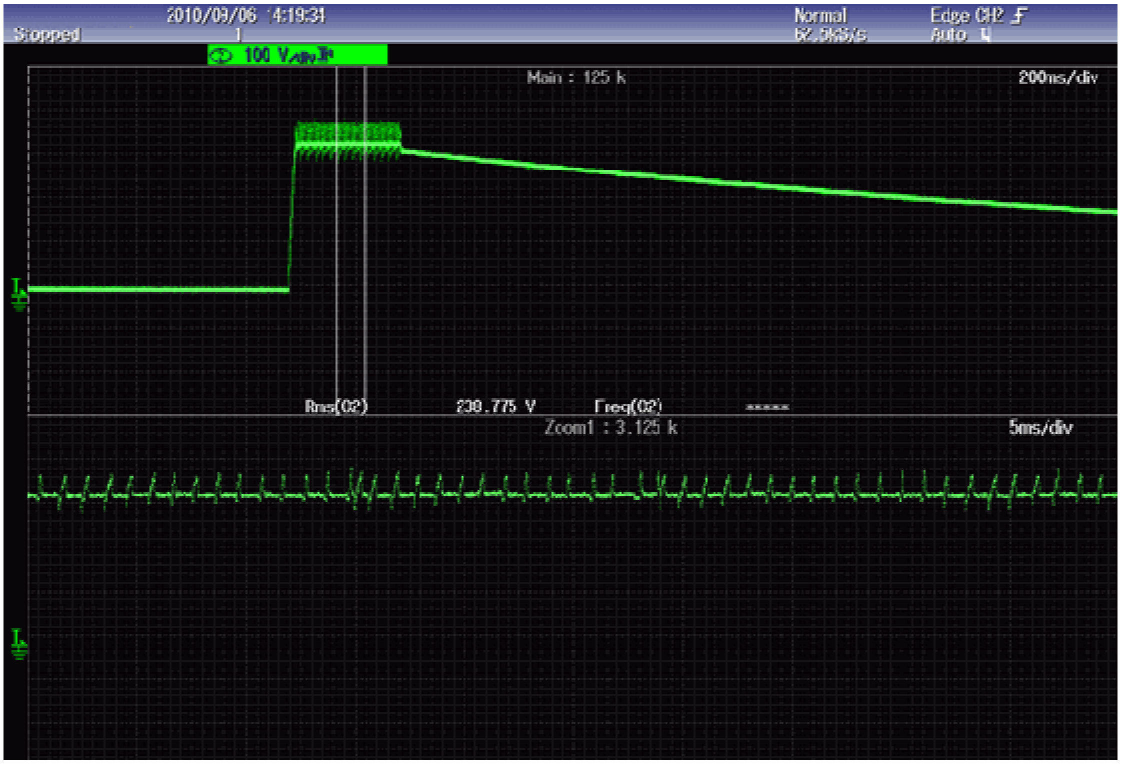
Voltage scale: 10kv/div Time scale: 500ns/div

FIGURE 29: INPUT CURRENT DURING START-UP PROCESS ON A COLD LAMP



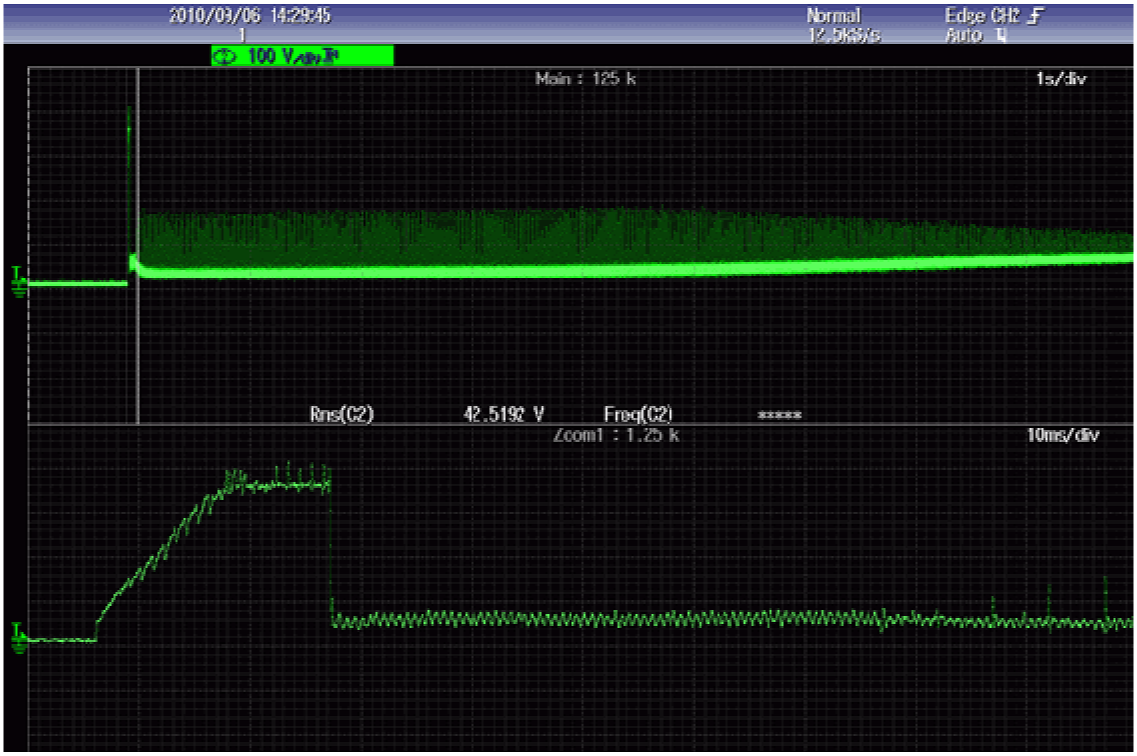
Current scale: 2A/div Time scale: 2s/div

FIGURE 30: OPEN VOLTAGE WAVEFORM AND IGNITION FAILED PROTECTION



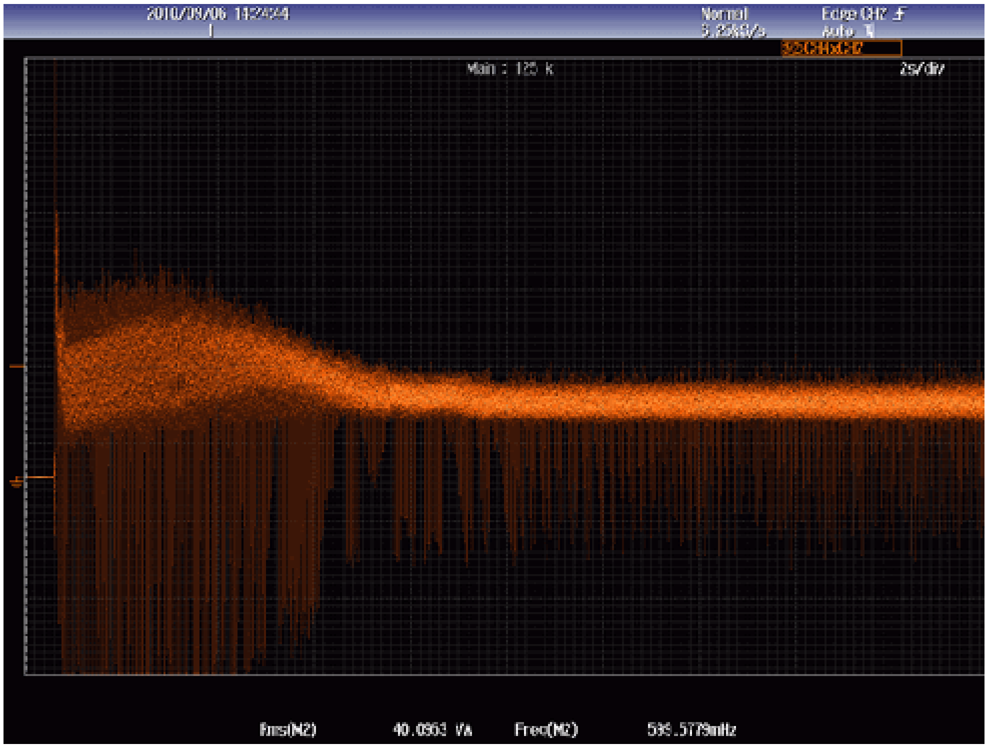
Voltage scale: 100V/div Time scale: 200ms/div, 5ms/div

FIGURE 31: DC BUS VOLTAGE (SUCCESSFUL IGNITION) OF BREAKOVER POINT



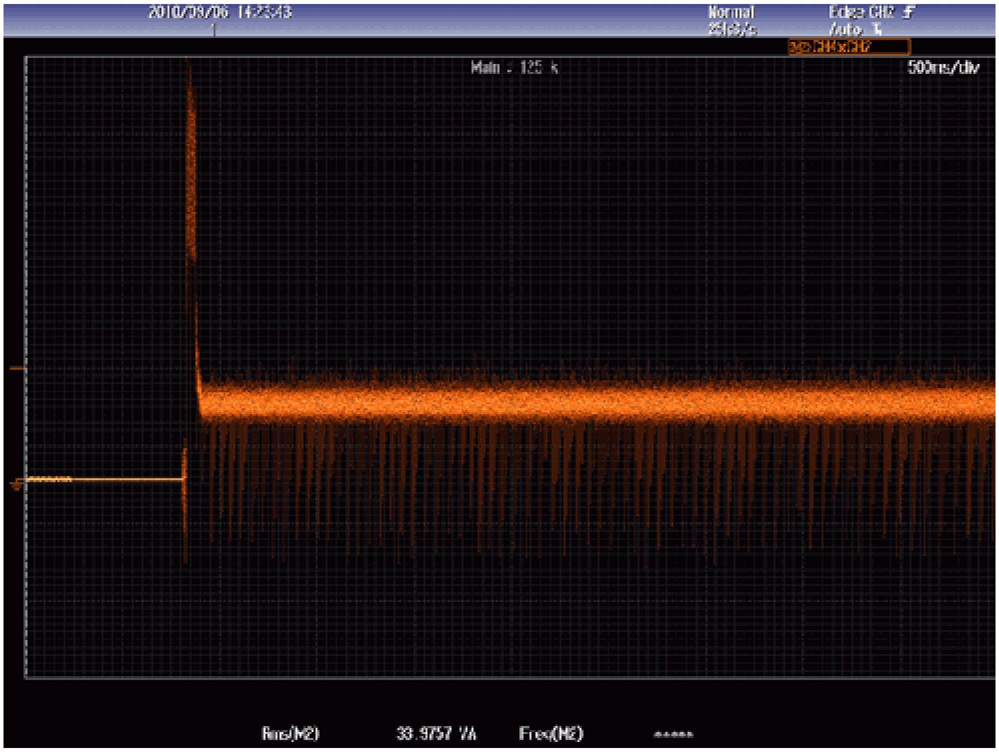
Voltage scale: 100V/div Time scale: 1s/div, 10ms/div

FIGURE 32: LAMP POWER WAVEFORM OF COLD LAMP



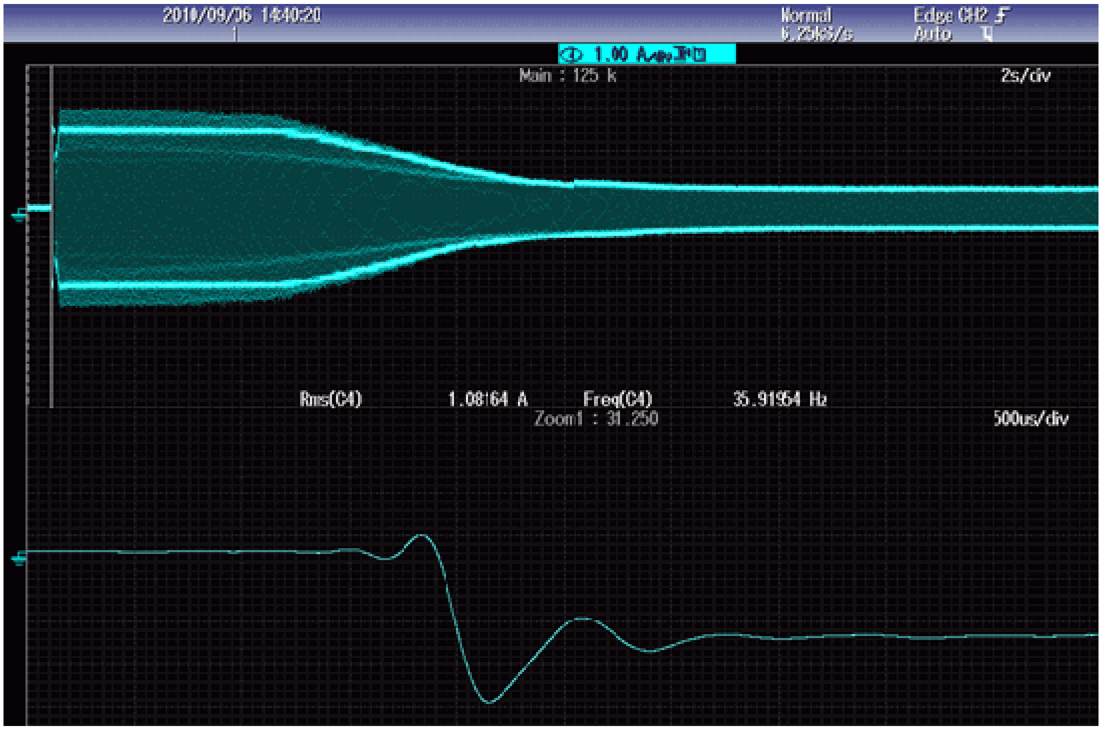
Power scale: 30W/div Time scale: 2s/div

FIGURE 33: LAMP POWER WAVEFORM OF HOT LAMP



Power scale: 30W/div Time scale: 500ms/div

FIGURE 34: CURRENT FOR COLD LAMP; ZOOM OF THE TAKE-CURRENT

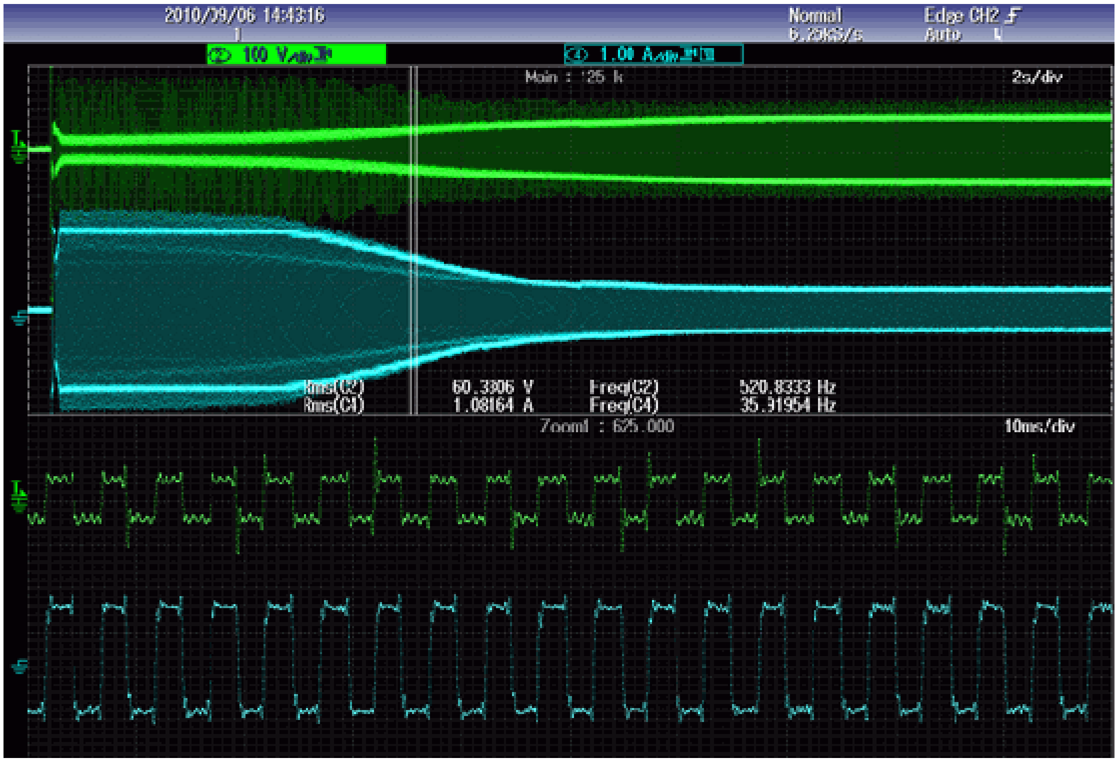


Current scale: 1A/div Time scale: 2s/div, 500us/div

FIGURE 35: CURRENT AND VOLTAGE FOR COLD LAMP; ZOOM OF THE DC WARM-UP CURRENT

Voltage scale: 100V/div Current scale: 1A/div Time scale: 2s/div, 10ms/div

FIGURE 36: CURRENT AND VOLTAGE FOR COLD LAMP; ZOOM OF THE RUN-UP STAGE



Voltage scale: 100V/div Current scale: 1A/div Time scale: 2s/div, 10ms/div

FIGURE 37: CURRENT AND VOLTAGE FOR COLD LAMP; ZOOM OF THE STEADY STATE

Voltage scale: 100V/div Current scale: 1A/div Time scale: 2s/div, 10ms/div

SUMMARY

The reference design presented in this application note shows a complete fully digital controlled HID ballast design with simple circuitry and fast response. The Microchip dsPIC DSC device used in this reference design provides all of the necessary features and peripherals to implement a high-performance HID ballast. Its 40 MHz DSP engine is fast enough to implement real-time power loop control. Together with the on-chip Intelligence power peripheral modules (High-Speed ADC, Comparator, PWM), different control loops combined with precise timing control was easily implemented. Fast and smooth transition between different loops was also developed. The initial arc was successfully detected, and the subsequent fast response was provided to maintain it. In addition, system diagnose and fault protection can also be implemented without extra components.

Note:	Future plans for this application note include the addition of MATLAB modeling information. Please continue to check the Microchip web site for updates.

APPENDIX A: SOURCE CODE

All of the software covered in this application note is available as a single WinZip archive file. This archive can be downloaded from the Microchip corporate Web site at:

www.microchip.com

APPENDIX B: SCHEMATICS AND BOARD LAYOUT

FIGURE B-1: BALLAST SCHEMATIC

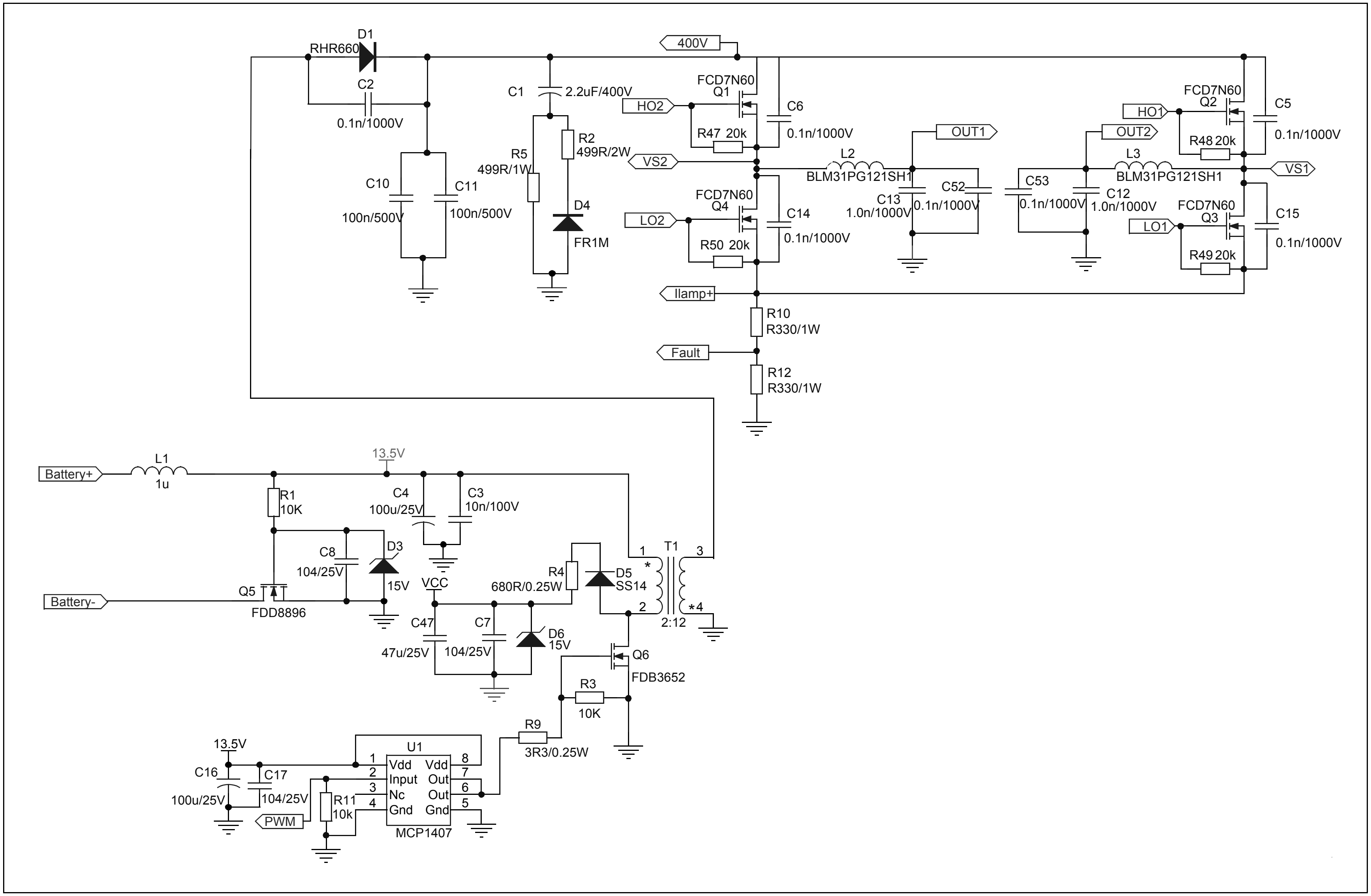


FIGURE B-2: dsPIC® DSC DEVICE SCHEMATIC

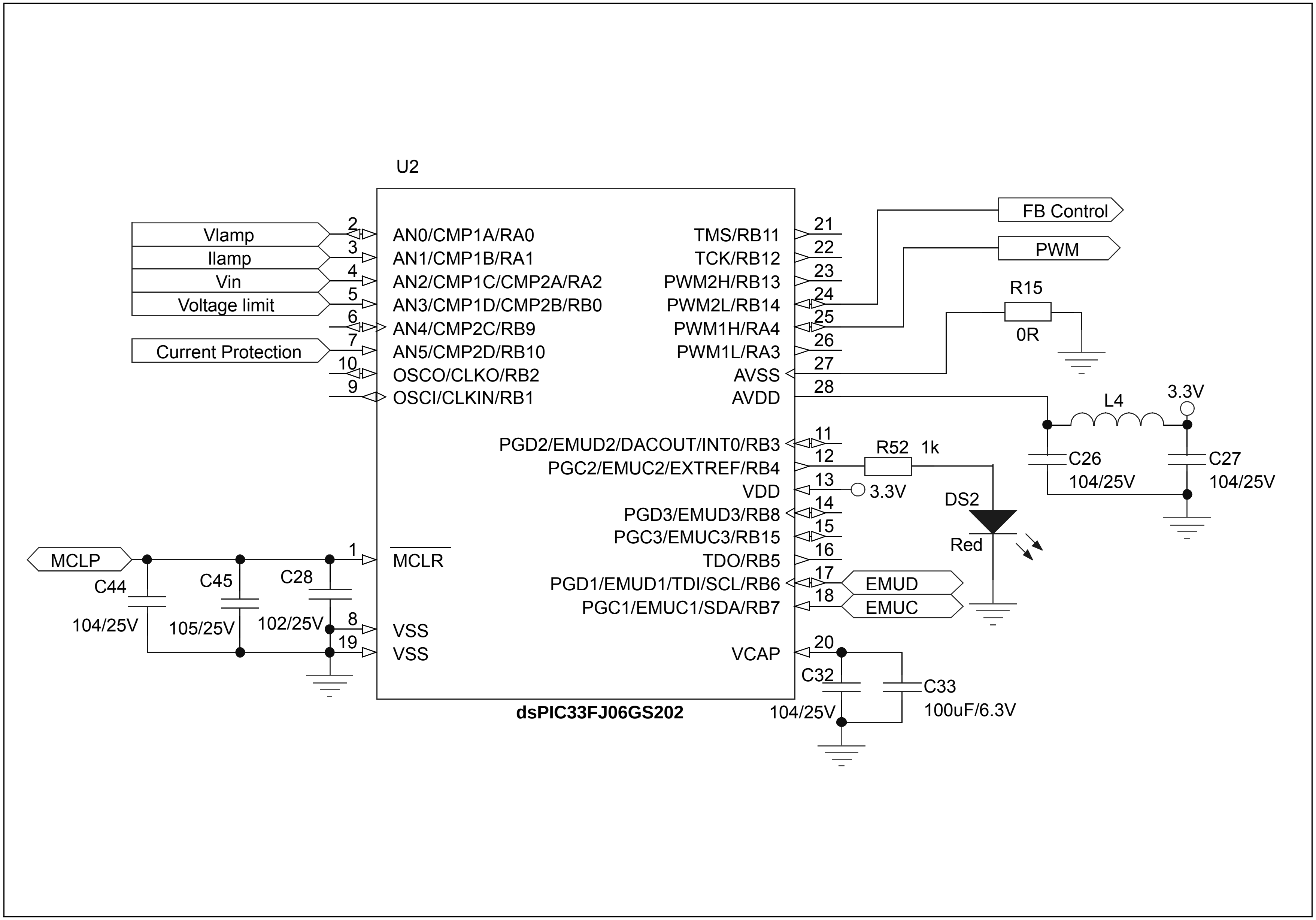


FIGURE B-3: POWER SUPPLY SCHEMATIC

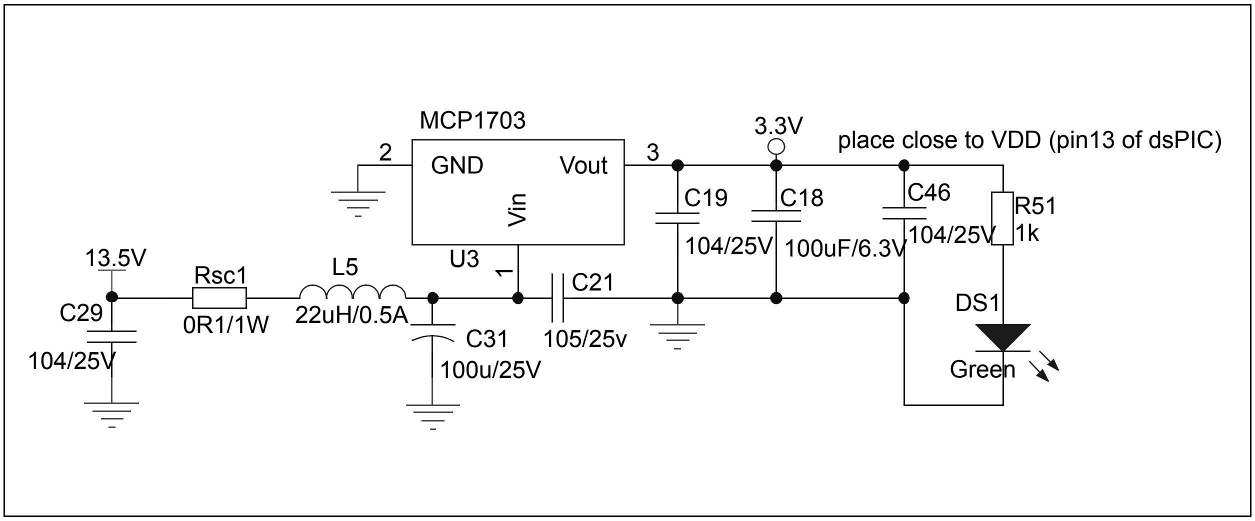


FIGURE B-4: MOSFET DRIVER SCHEMATIC

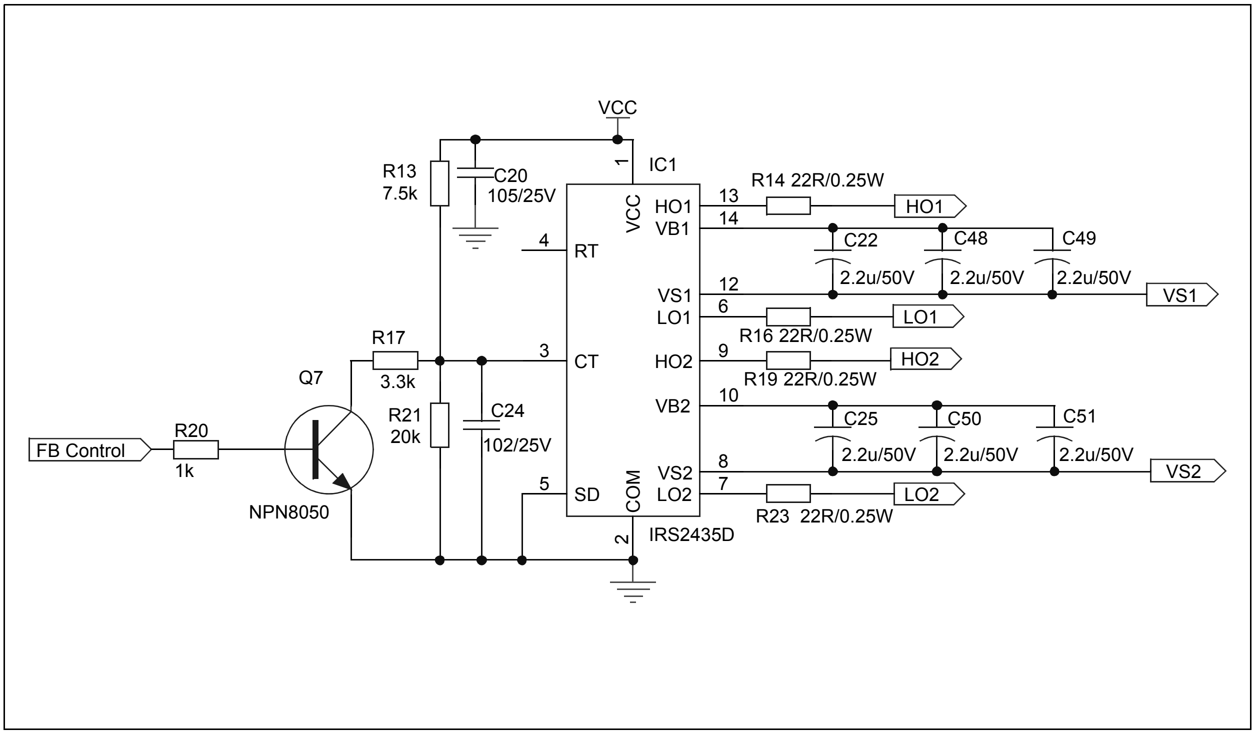
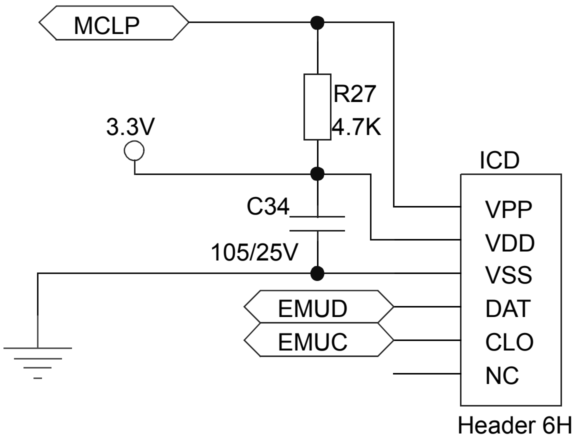
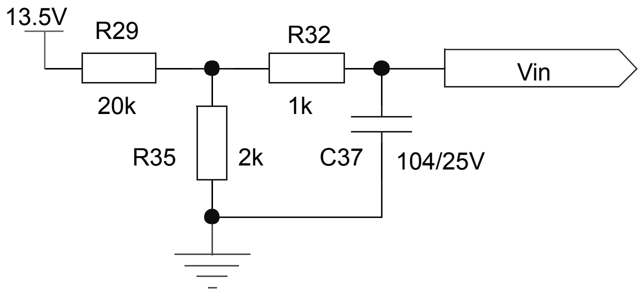


FIGURE B-5: DEBUGGER, INPUT VOLTAGE, AND OVERCURRENT SCHEMATICS

Debugger



Input Voltage



Overcurrent

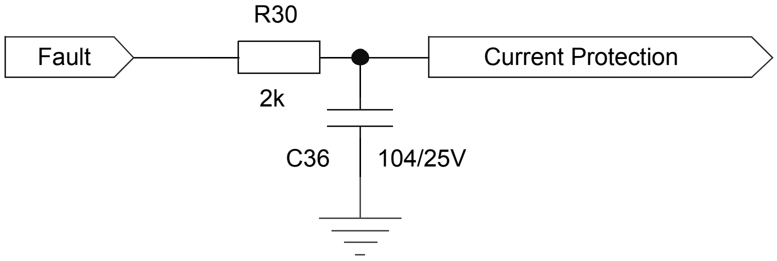
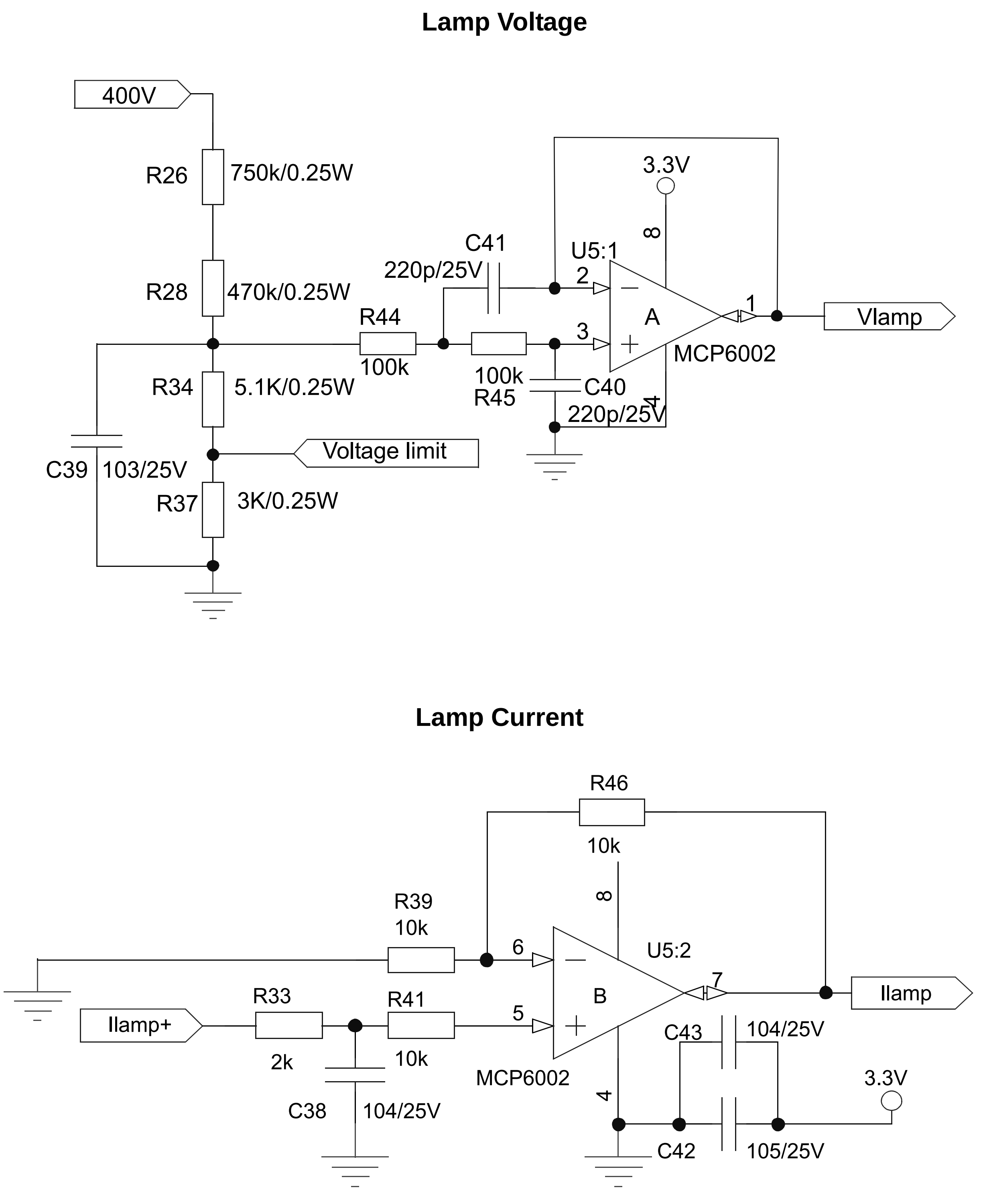


FIGURE B-6: LAMP VOLTAGE AND LAMP CURRENT SCHEMATICS



Lamp Voltage

Lamp Current

FIGURE B-7: IGNITER CIRCUIT SCHEMATIC

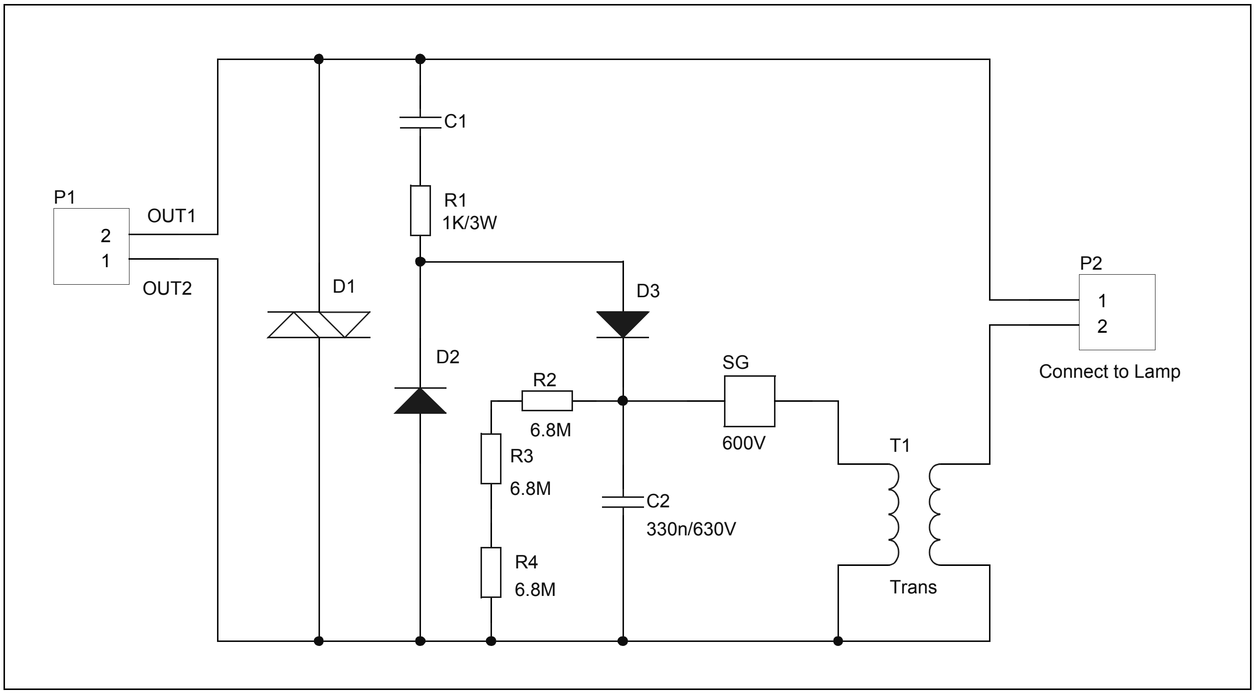


FIGURE B-8: BALLAST BOARD LAYOUT - TOP LAYER

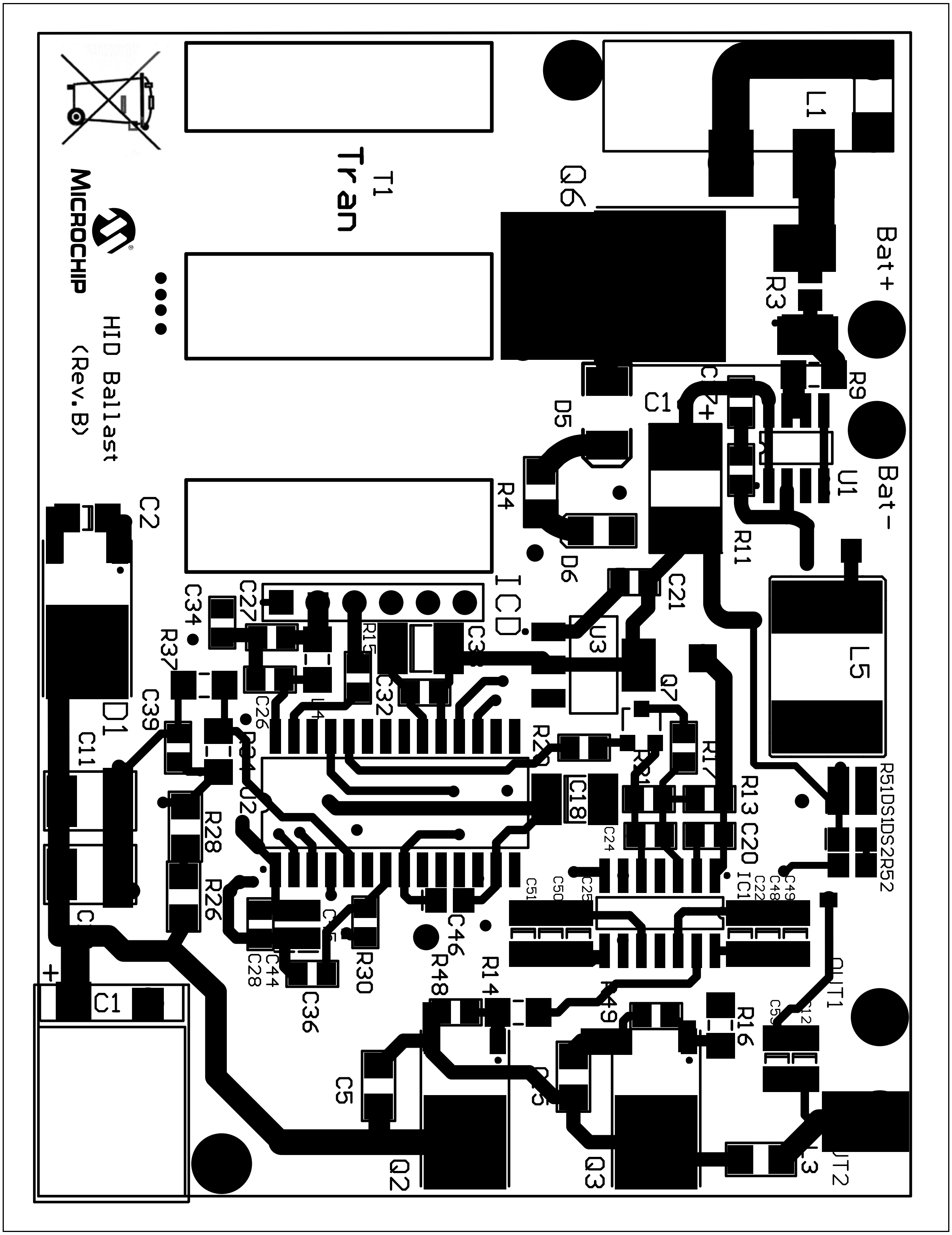


FIGURE B-9: BALLAST BOARD LAYOUT - MIDDLE LAYER 1

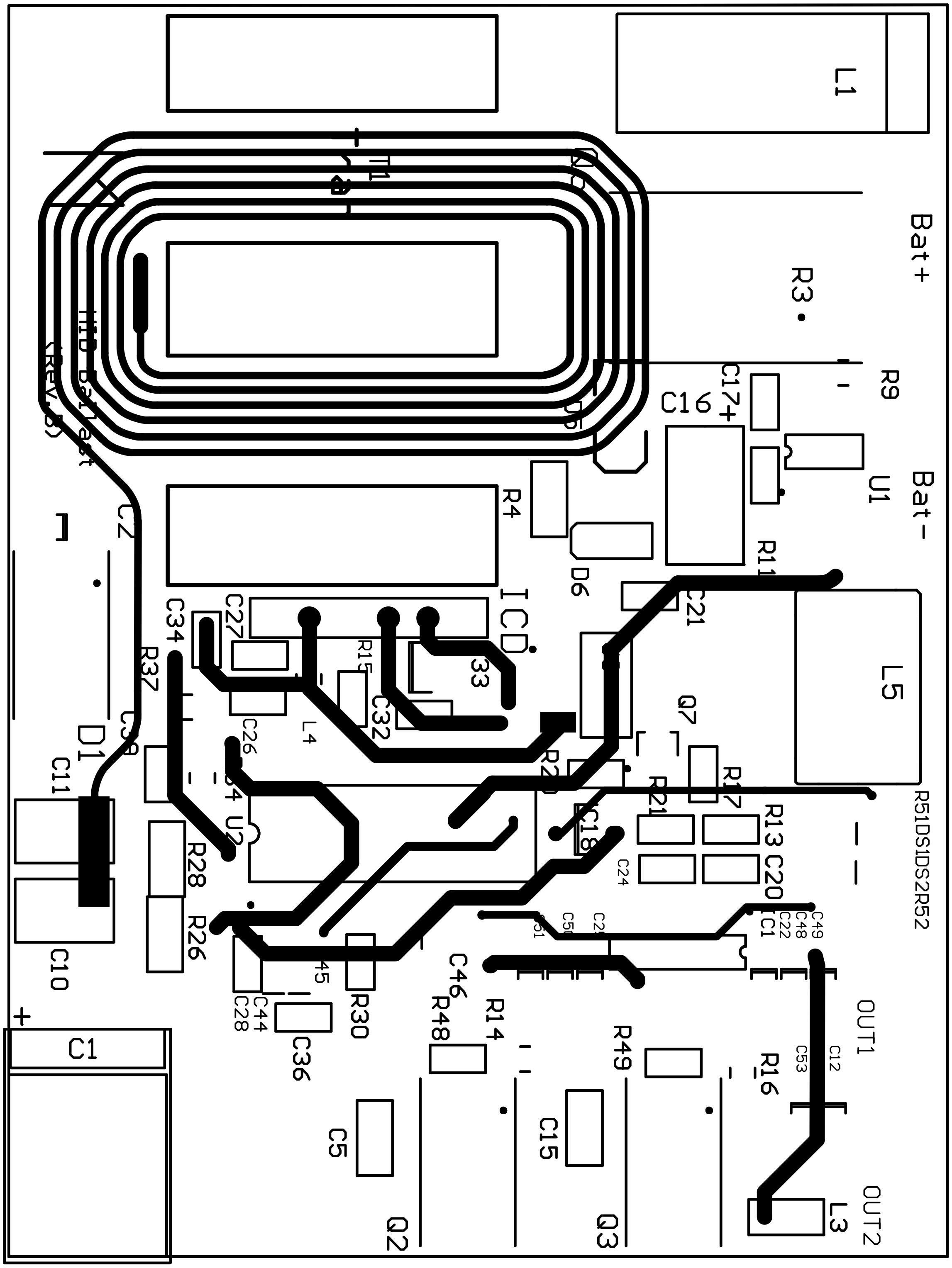


FIGURE B-10: BALLAST BOARD LAYOUT - MIDDLE LAYER 2

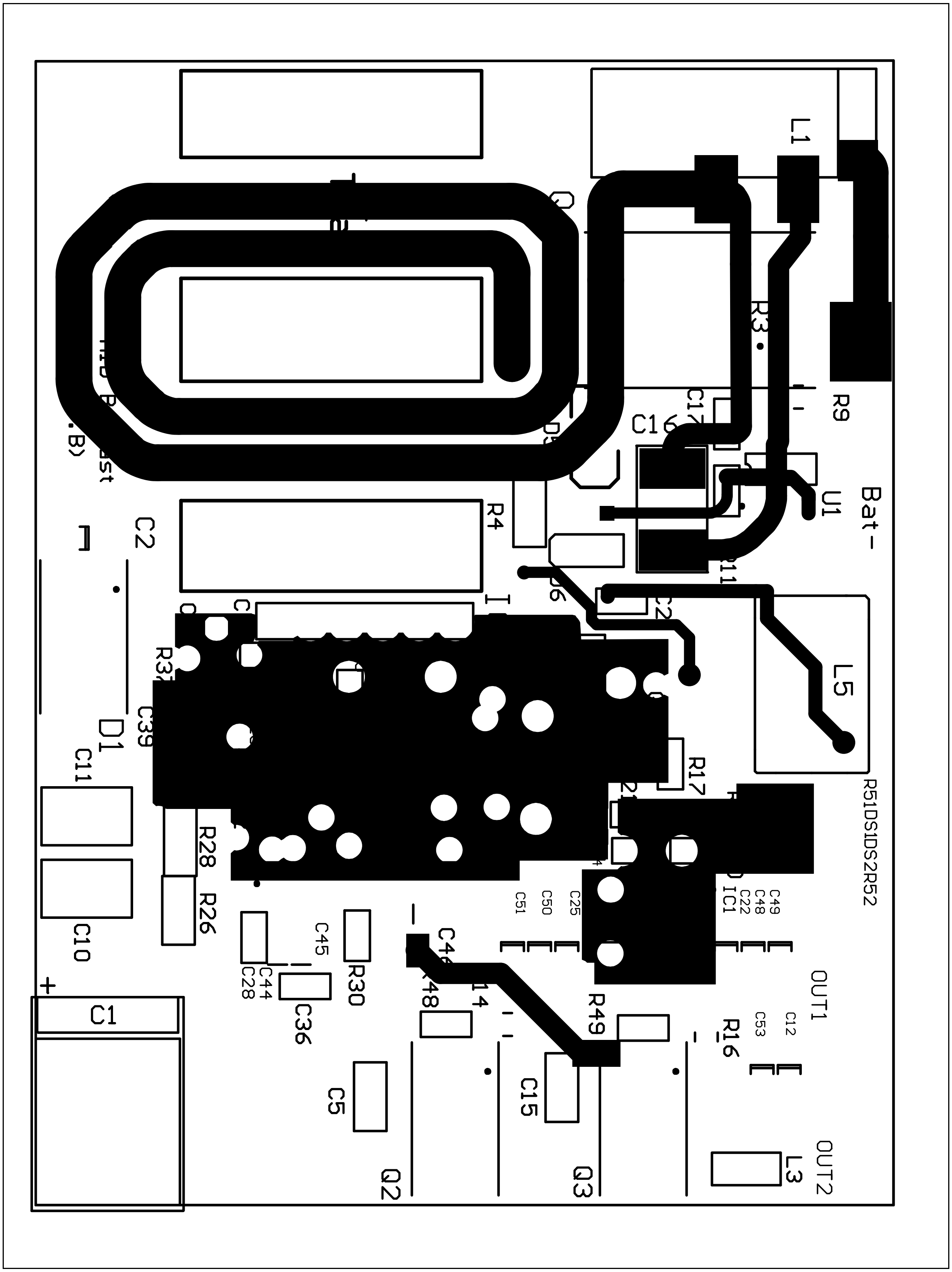


FIGURE B-11: BALLAST BOARD LAYOUT - BOTTOM LAYER

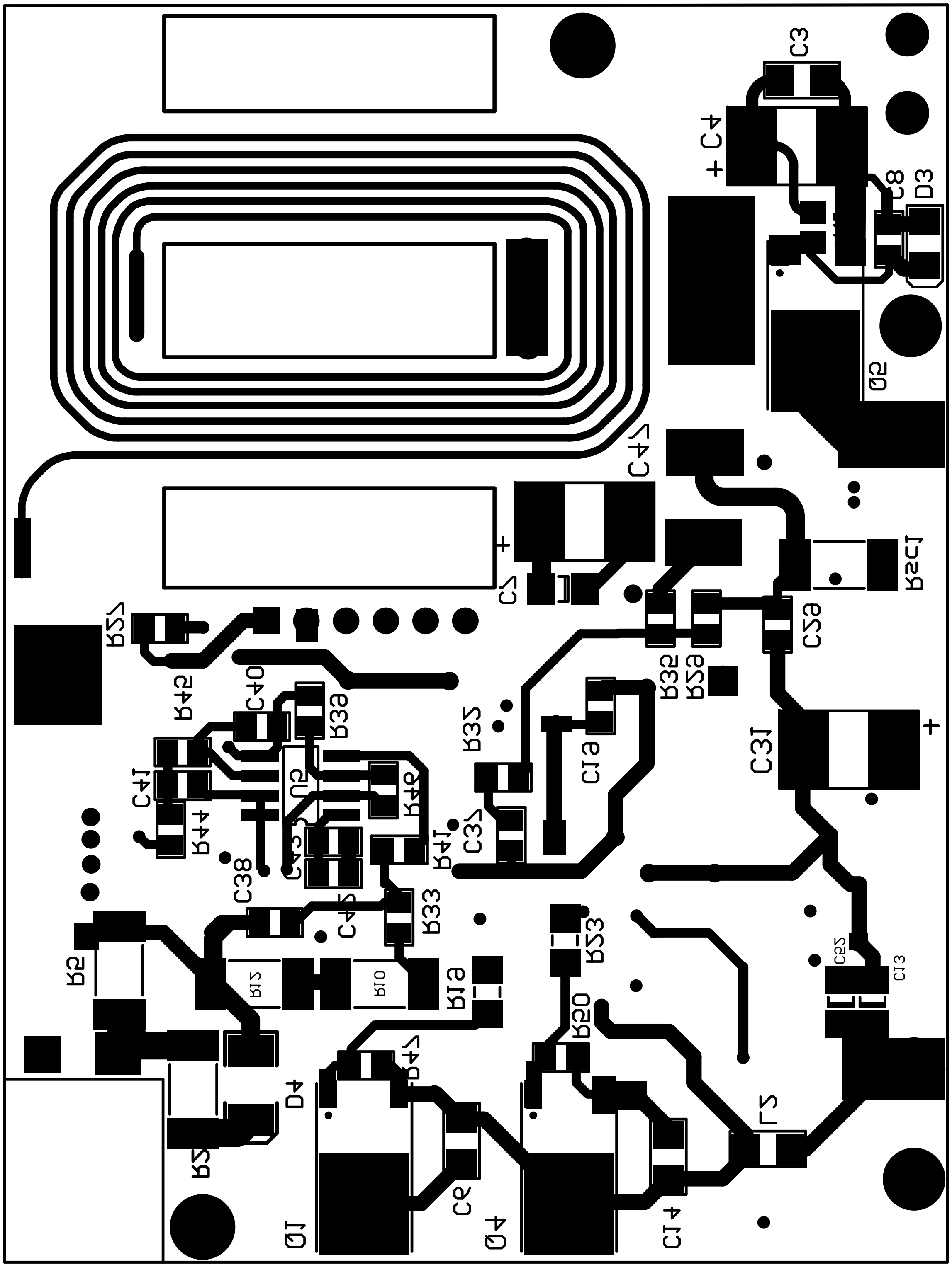


FIGURE B-12: BALLAST BOARD LAYOUT - TOP SIDE

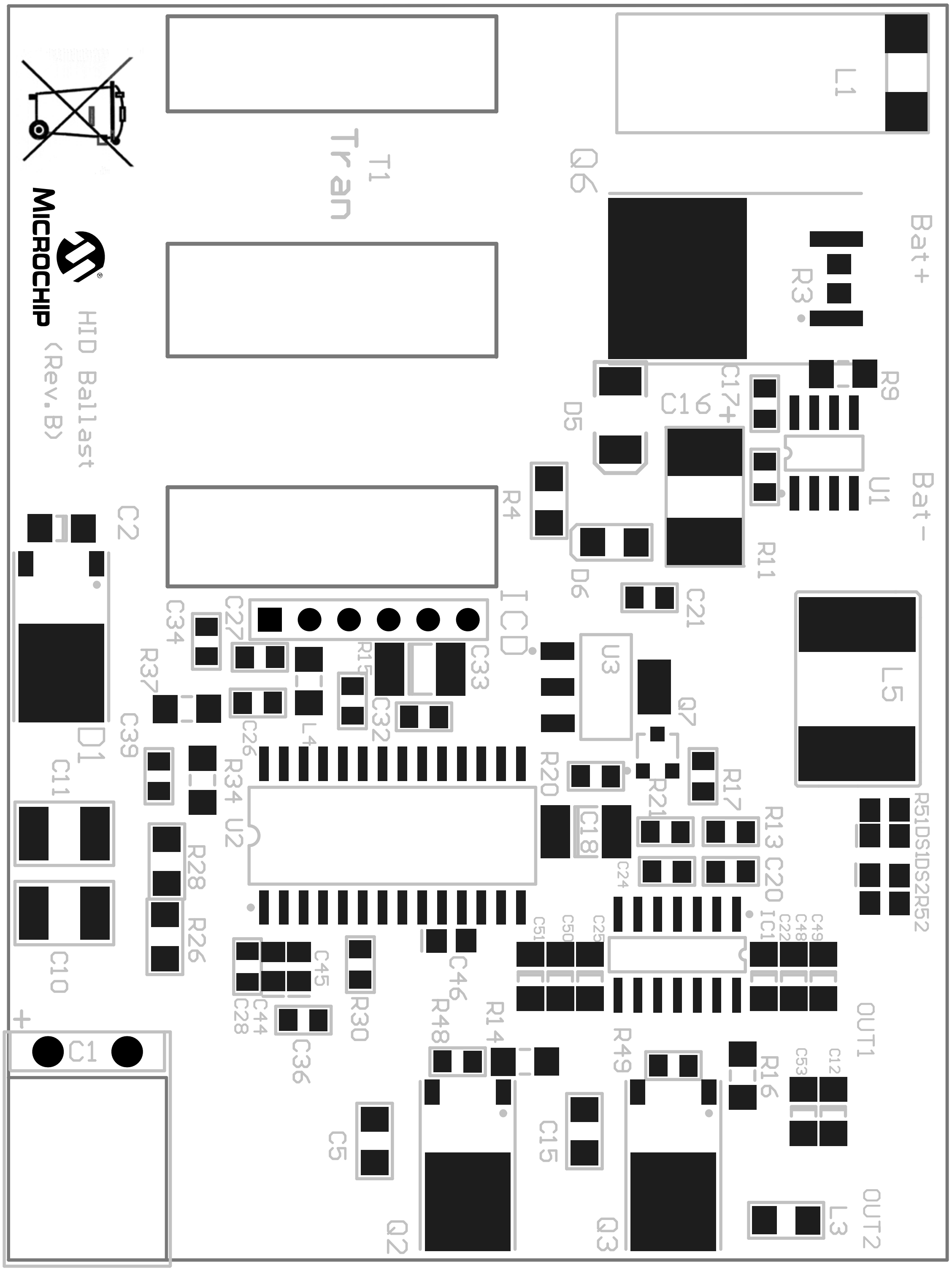
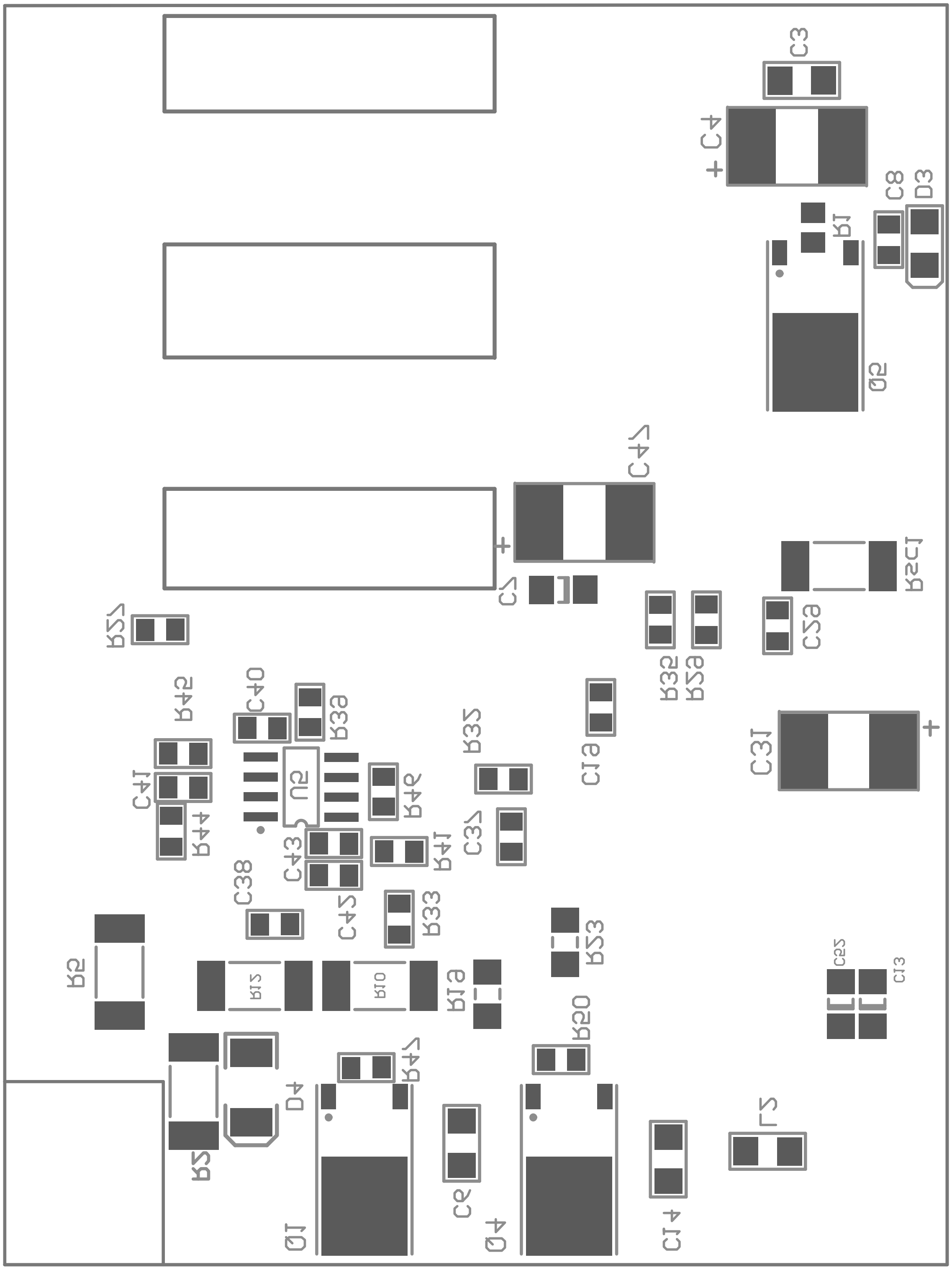


FIGURE B-13: BALLAST BOARD LAYOUT - BOTTOM SIDE



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