

250 W HID metal halide electronic ballast

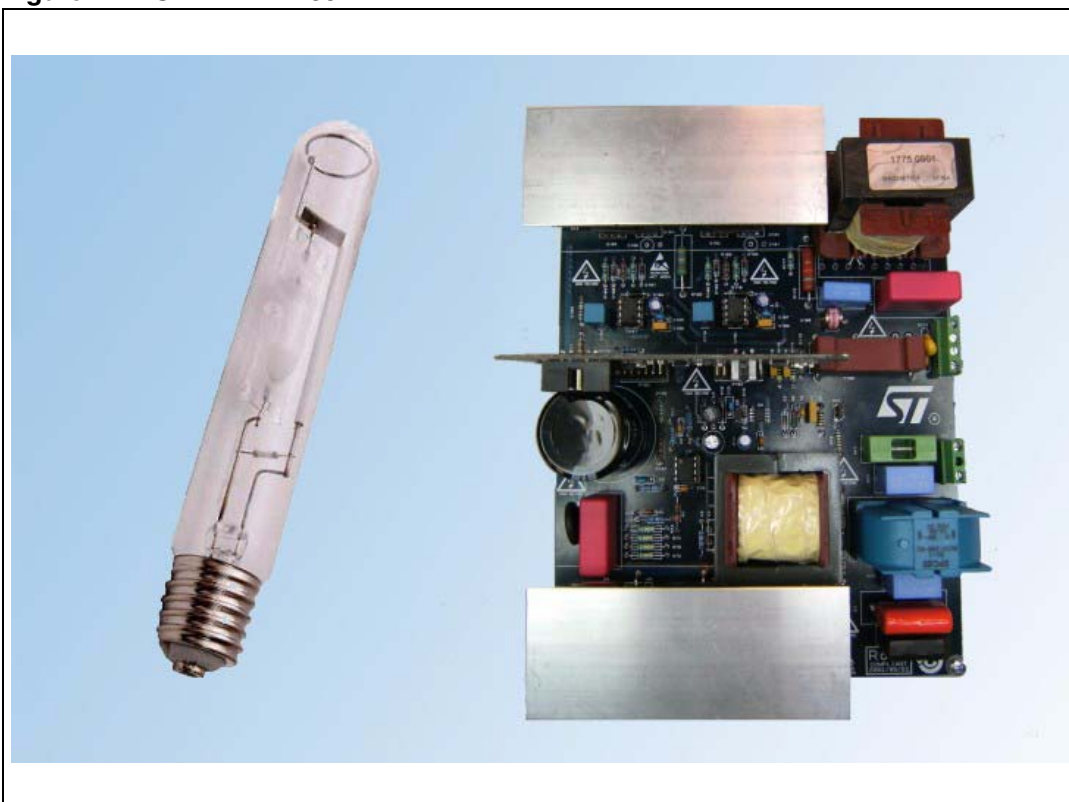
Introduction

This application note describes the two stages of electronic ballast for a 250 W HID metal halide lamp. The ballast is composed of a boost converter (power factor controller PFC) working in fixed OFF time and an inverter composed of a full bridge that drives the lamp at low frequency square wave.

This design was realized thanks to the very large STMicroelectronics product portfolio. The components include a PFC driver, half-bridge drivers, a microcontroller, an auxiliary power supply, a voltage reference, logic parts, an amplifier, comparators, power devices as Power MOSFETs, IGBTs, and fast diodes.

In the present note special attention has been given to the full bridge stage. The tests have been conducted using a 250 W metal halide lamp HQI - T (OSRAM) and some design criteria are given with test results. In the full bridge section all lamp phases have been analyzed.

Figure 1. STEVAL-ILH001V1



Contents

1	Lamp description	5
1.1	Lamp phases	7
1.1.1	Ignition phase	7
1.1.2	Warm-up	7
1.1.3	Burn phase	8
2	General circuit description	9
2.1	Block diagram	9
2.2	Lamp power management	10
3	Board description	12
3.1	Electrical schematic	12
3.2	Bill of material	16
4	L6385 high-voltage high and low side driver	20
5	ST7LITE39 microcontroller	21
5.1	Application pins	22
6	Auxiliary power supply	27
7	TS272 high-performance CMOS dual operational amplifiers	28
8	LM119 high-speed dual comparators	29
9	74AC00 QUAD2-input NAND gates	30
10	Lamp data	31
11	PFC section design criteria	32
12	Full bridge design criteria	32
12.0.1	Inductor design	32
12.1	Filter capacitor	32
12.2	Igniter	33

12.3	Power MOSFET selection	34
12.4	IGBT selection	34
13	Experimental results	36
13.1	Init phase	36
13.2	Lamp ignition phase	37
13.3	Warm-up phase	37
13.4	Burn phase	38
13.5	PFC run phase	39
13.6	Thermal measurement	40
14	Firmware flowchart	40
15	References	42
16	Revision history	43

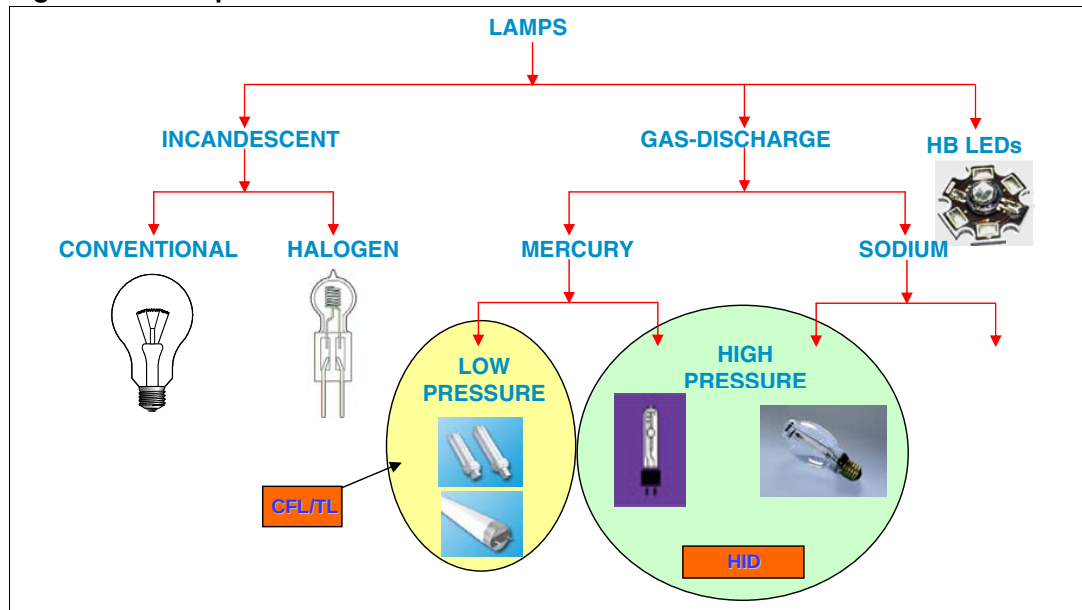
List of figures

Figure 1.	STEVAL-ILH001V1	1
Figure 2.	Lamp families	5
Figure 3.	Luminous efficiency of various lamps	5
Figure 4.	HID lamps operation frequency: high pressure sodium lamps - acoustic resonance duty frequency map	6
Figure 5.	HID lamps operation frequency: metal halide lamps - acoustic resonance duty frequency map	6
Figure 6.	Instantaneous lamp power with sinusoidal and square waveforms	7
Figure 7.	HID warm-up phase	8
Figure 8.	250 W HID lamp ballast - block diagram	9
Figure 9.	Inductor current during charge phase	9
Figure 10.	Inductor current during discharge phase	10
Figure 11.	PFC electrical schematic	12
Figure 12.	Full bridge electrical schematic	13
Figure 13.	Control board electrical schematic	14
Figure 14.	Power board layout (not to scale)	15
Figure 15.	Control board layout (not to scale)	15
Figure 16.	L6385 block diagram	20
Figure 17.	ST7FLIT3xB general block diagram	21
Figure 18.	ST7FLITE39 pinout	22
Figure 19.	MU reference voltage circuit	22
Figure 20.	Pin usage and reset circuit	23
Figure 21.	Vbus measurement circuit	23
Figure 22.	Lamp voltage sensing circuit	24
Figure 23.	Lamp voltage measurement circuit	24
Figure 24.	Constant current control	25
Figure 25.	Rsense circuit	25
Figure 26.	Current regulation circuit	26
Figure 27.	Auxiliary power supply	27
Figure 28.	Pinout	28
Figure 29.	LM119 pinout	29
Figure 30.	74AC00 pinout	30
Figure 31.	Eye sensitivity versus frequency	31
Figure 32.	Igniter circuit	33
Figure 33.	Full bridge init phase	36
Figure 34.	Lamp ignition voltage	37
Figure 35.	Lamp current and voltage during warm-up phase	38
Figure 36.	Warm-up phase	38
Figure 37.	Steady state phase: lamp current, voltage and lamp power	39
Figure 38.	Steady state phase: lamp current, voltage and lamp power	39
Figure 39.	Ballast efficiency	40
Figure 40.	Firmware flowchart	41

1 Lamp description

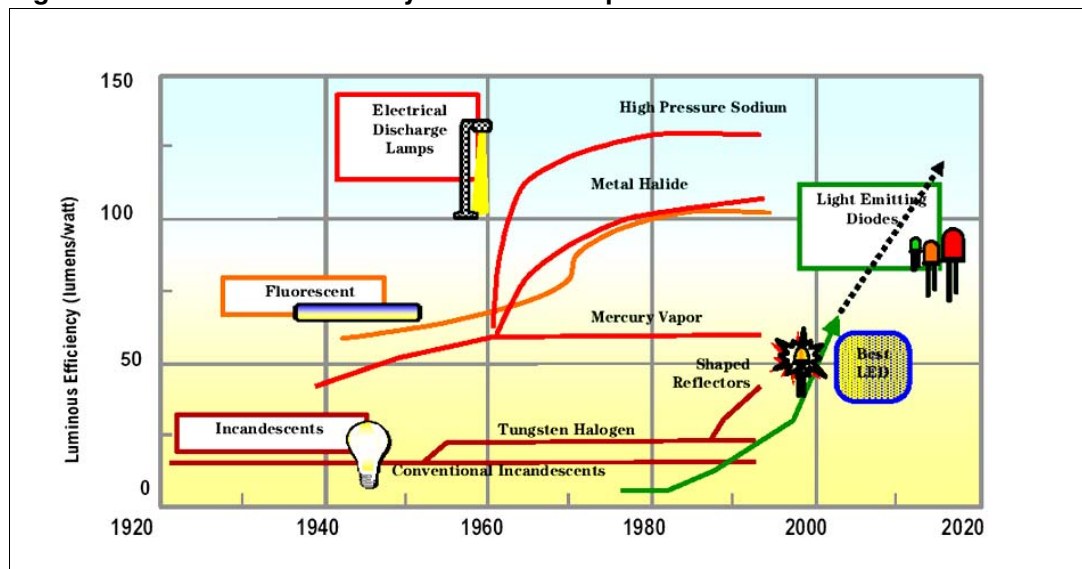
New products and devices are being launched in lighting applications and new solutions for these applications are required. High intensity discharge (HID) lamps have become attractive lighting sources for their luminous efficacy and their long life. [Figure 2](#) illustrates the families of electric lighting for which HID lamps are intended.

Figure 2. Lamp families



In this document we will refer to high pressure sodium and mercury lamps as HID lamps. [Figure 3](#) shows the luminous efficiency for each lamp type.

Figure 3. Luminous efficiency of various lamps



Referring to [Figure 3](#) we can see that HID lamps have higher luminous efficacy, but some negative aspects must be considered.

When comparing HID and fluorescent lamps, two important issues should be considered: a greater starting voltage and the presence of acoustic resonance.

To solve the issue of higher HID ignition voltage, a sort of starting aid, called igniters, are used to ignite the lamp.

The problem of acoustic resonance is more complex. Acoustic resonance is characteristic of HID lamps operating at frequencies greater than 1 kHz and appears when lamp power fluctuation exceeds a threshold value.

The current/voltage lamp waveforms and the operating frequency cannot be chosen freely, but they are dependent on lamp type, condition and temperature. A wrong choice of frequency and/or waveform can have a very negative effect on lamp performance and/or lifetime and sometimes the discharge tube may be mechanically damaged.

Figure 4. HID lamps operation frequency: high pressure sodium lamps - acoustic resonance duty frequency map

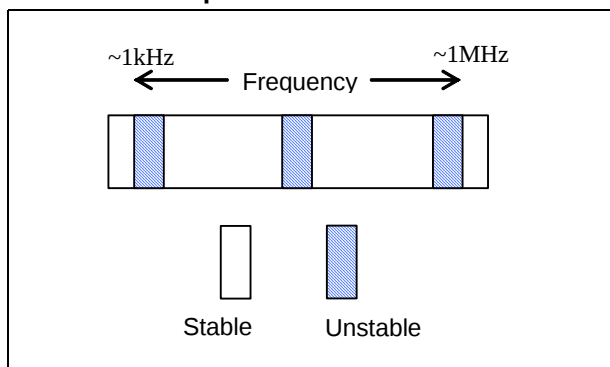
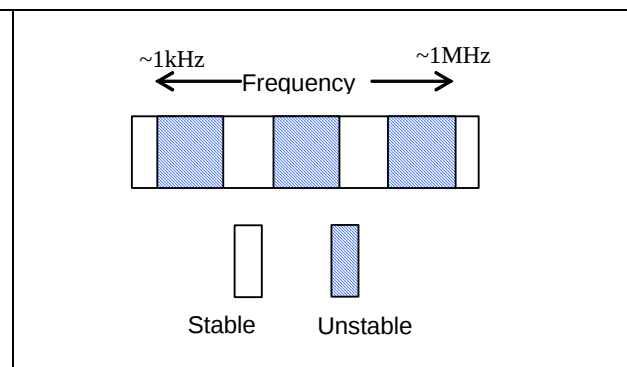


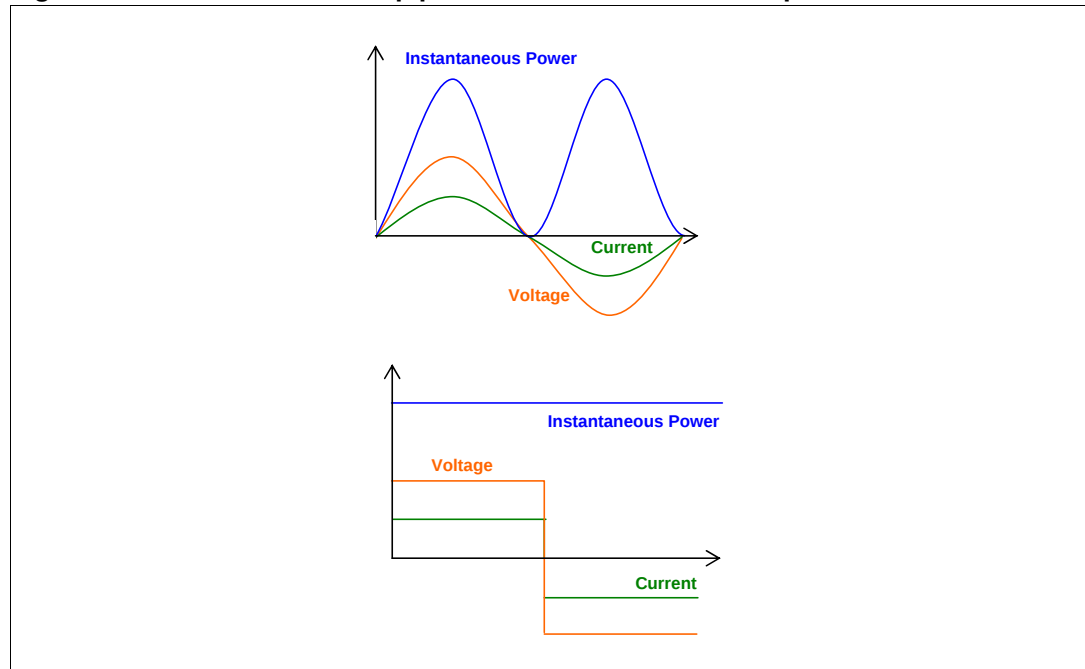
Figure 5. HID lamps operation frequency: metal halide lamps - acoustic resonance duty frequency map



As shown in [Figure 4](#) and [5](#) for different lamps the free bands are completely different.

- For HID lamps the solution proposed to avoid acoustic resonance uses the same principle. The designer must avoid a combination of power fluctuation and operating frequency. Another parameter that must be taken into account is flickering. For this reason, the frequency used in the application is higher than 100 Hz and below 1 kHz.

For sinusoidal waveforms the instant lamp power is variable and it has twice the frequency of the voltage and current frequency. In [Figure 6](#) a diagram of instantaneous power for different waveforms is shown.

Figure 6. Instantaneous lamp power with sinusoidal and square waveforms

For ideal square waveforms, the instant power delivered to the lamp is constant and not modulated by any frequency. This driving plus the low frequency driving allows obtaining a system that is immune to the problem of acoustic resonance.

For this reason HID lamp applications using square wave current techniques are the best solution.

1.1 Lamp phases

1.1.1 Ignition phase

The ignition voltage for HID lamps is higher with respect to the mains voltage. The peak voltage value to initiate the discharge is very high. Typically this is about $3\text{ kV} \div 5\text{ kV}$.

The voltage level at which an HID lamp ignites is called "ignition voltage". This voltage level is referred to the lamp when it is cold but this value increases with lamp temperature.

To ensure immediate HID lamp restart, called "hot restrike", very high re-ignition peaks are necessary (about 20 kV).

Standard luminaries are not designed for hot restrike voltages. For this reason in order to obtain hot lamp re-ignition, several minutes must elapse for the lamp to cool. The restart time depends on lamp temperature.

1.1.2 Warm-up

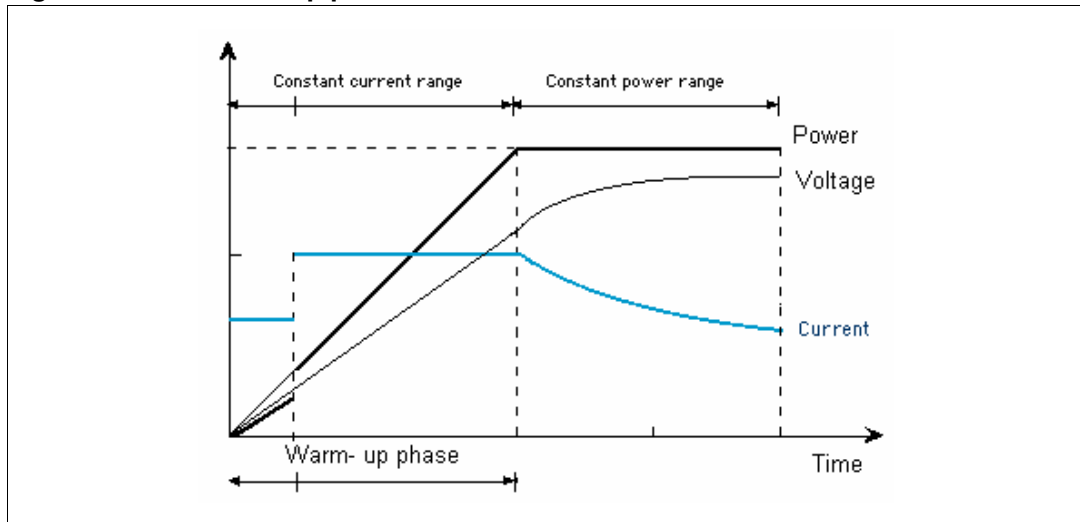
When the discharge has been initiated by the starting gas and the lamp still does not burn properly, a warm-up time is required.

During the warm-up time the gas temperature increases, increasing the light output. The lamp voltage starts approximately from a quarter of V_{lamp} and increases up to V_{lamp} .

During this phase the maximum current must be limited and maintained at a value higher than 30% of the nominal value. The time to reach 80% of full light/power is called “warm-up time”. HID lamps have a warm-up time of approximately 2-5 minutes.

In [Figure 7](#) typical behaviors of lamp voltage and current during warm-up is shown.

Figure 7. HID warm-up phase



1.1.3 Burn phase

After the warm-up phase when the lamp reaches nominal power, the lamp current must be regulated taking into account the lamp voltage to ensure fixed rated power.

2 General circuit description

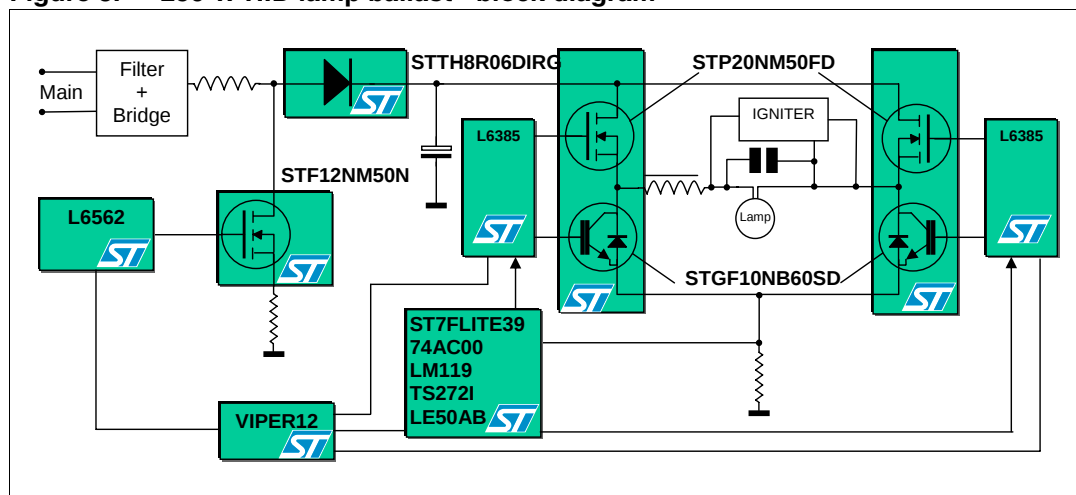
2.1 Block diagram

The block diagram of the ballast is shown in [Figure 8](#). The complete circuit is composed of two stages:

- The boost converter which regulates the output voltage and performs the power factor correction.
- The inverter stage composed of a full bridge that converts the DC current coming from the PFC stage into an AC current for the lamp.

The operation mode of the full bridge realizes a synchronous buck converter. The full bridge moreover drives the igniter block to generate the high-voltage pulses.

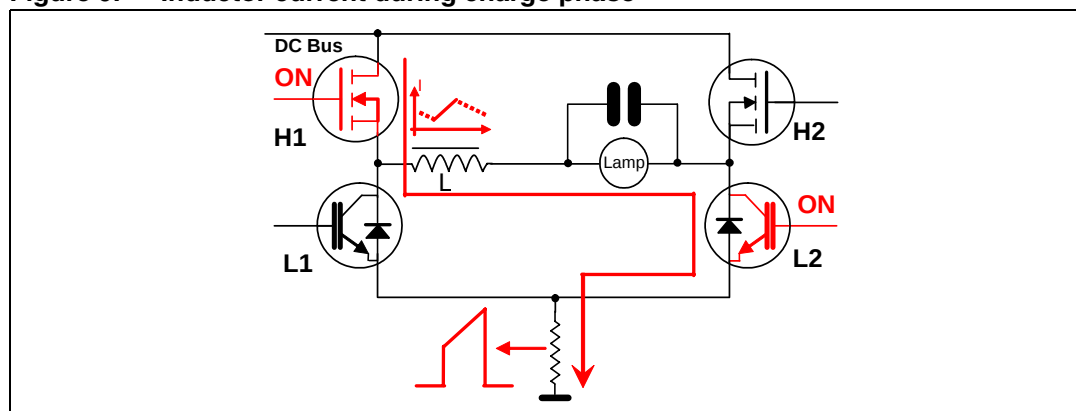
Figure 8. 250 W HID lamp ballast - block diagram



To generate a square wave current in the lamp, the circuit is driven in the following way:

- a) When low side device L2 is switched ON, the high side Power MOSFET H1 operates with a high-frequency pulse width modulation (PWM). The duty cycle D is established by a constant-current control circuit.

Figure 9. Inductor current during charge phase



In this condition the current increases linearly and the voltage across the inductor L is:

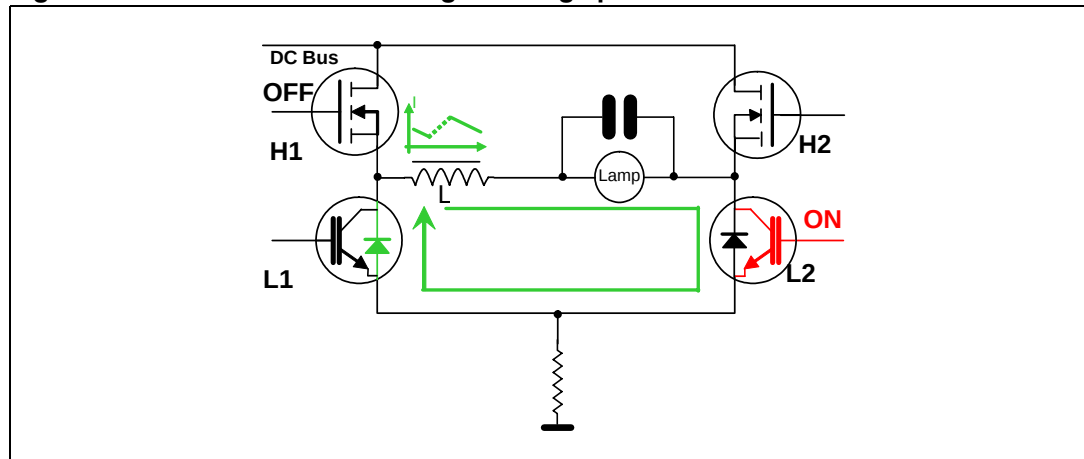
Equation 1

$$V_L = V_{dc} - V_{lamp}$$

where

- V_L = lamp voltage
 - V_{dc} = DC bus voltage
 - V_{lamp} = lamp voltage
- b) When the high side device H1 is switched OFF, the current flows in the low side devices. The freewheeling diode integrated in the low side device IGBT L1 operates at high frequency with duty cycle 1-D (see [Figure 10](#)).

Figure 10. Inductor current during discharge phase



The voltage across the inductor is:

Equation 2

$$V_L = -V_{lamp}$$

The current through L decreases linearly. This circuit is actually a synchronous rectifier buck converter. To minimize the current ripple through the lamp, the circuit operates in continuous conduction mode (CCM) with fixed frequency.

The circuit operates in mode A and B complementarily in low frequency supplying the lamp with square wave alternate current.

2.2 Lamp power management

The lamp power is obtained by multiplying the lamp voltage signal and the lamp current.

The lamp voltage is sensed directly across the lamp while the lamp current is obtained using the relation given below. In continuous mode the lamp current is coincident with average buck coil current. Starting from peak inductor current the average value is:

Equation 3

$$I_{lamp} = I_{AV} = I_{peak} - \frac{\Delta I}{2}$$

where

- I_{lamp} = lamp current
- I_{AV} = average current
- I_{peak} = inductor peak current
- ΔI = inductor current ripple

The ripple current in a buck converter working in continuous mode is expressed as:

Equation 4

$$\Delta I = \frac{V_{\text{bus}}}{f \cdot L} \cdot \delta \cdot (1 - \delta)$$

where

- V_{bus} = DC bus voltage
- L = inductance value
- f = switching frequency
- ζ = duty cycle

For the buck in continuous mode the duty cycle relation is:

Equation 5

$$\delta = \frac{V_{\text{lamp}}}{V_{\text{bus}}}$$

Using the relation ([Equation 4](#)) in the equation ([5](#)) we obtain:

Equation 6

$$\frac{\Delta I}{2} = \frac{1}{2 \cdot f \cdot L \cdot V_{\text{bus}}} \cdot V_{\text{lamp}} \cdot (V_{\text{bus}} - V_{\text{lamp}})$$

Assuming V_{bus} and f constant it is possible to write:

Equation 7

$$K = \frac{1}{2 \cdot f \cdot L \cdot V_{\text{bus}}}$$

The relation ([Equation 3](#)) can be written as:

Equation 8

$$I_{\text{lamp}} = I_{\text{peak}} - K \cdot V_{\text{lamp}} \cdot (V_{\text{bus}} - V_{\text{lamp}})$$

This relation is valid because the average current is equal to the lamp current. This formula is implemented in the microcontroller in order to calculate the lamp current.

3 Board description

The detailed electrical schematics are given in the following figures.

3.1 Electrical schematic

Figure 11. PFC electrical schematic

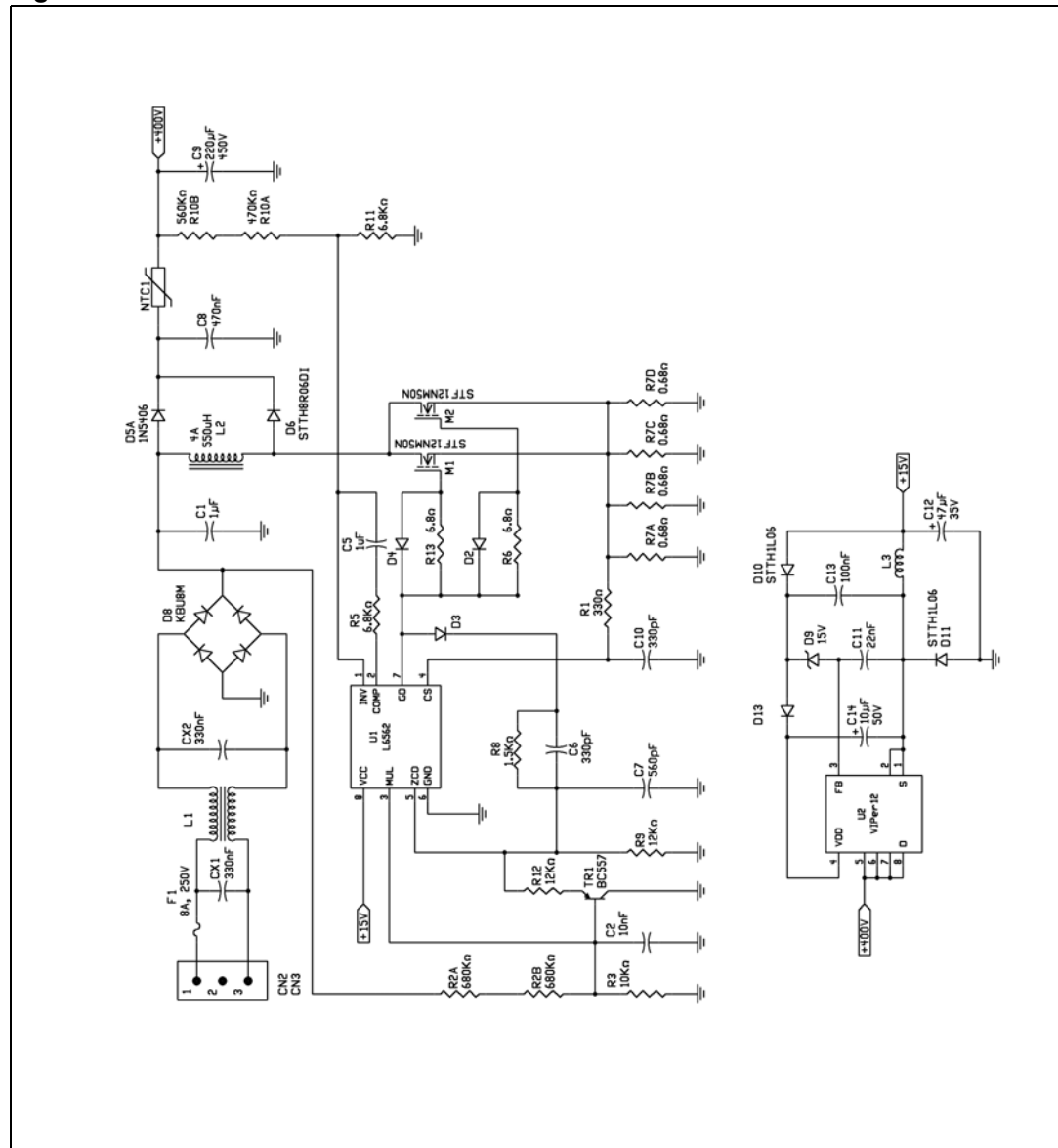


Figure 12. Full bridge electrical schematic

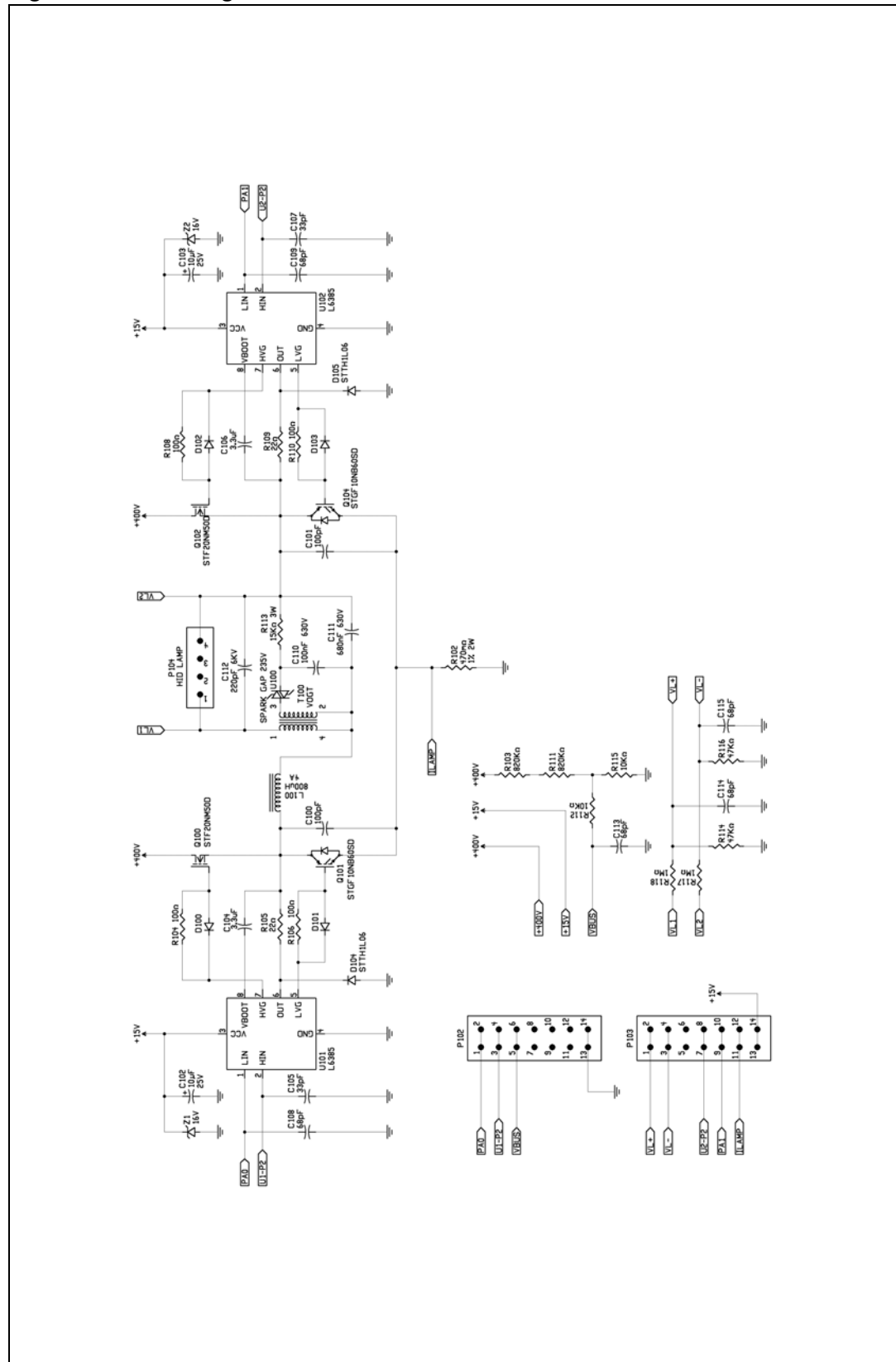


Figure 14. Power board layout (not to scale)

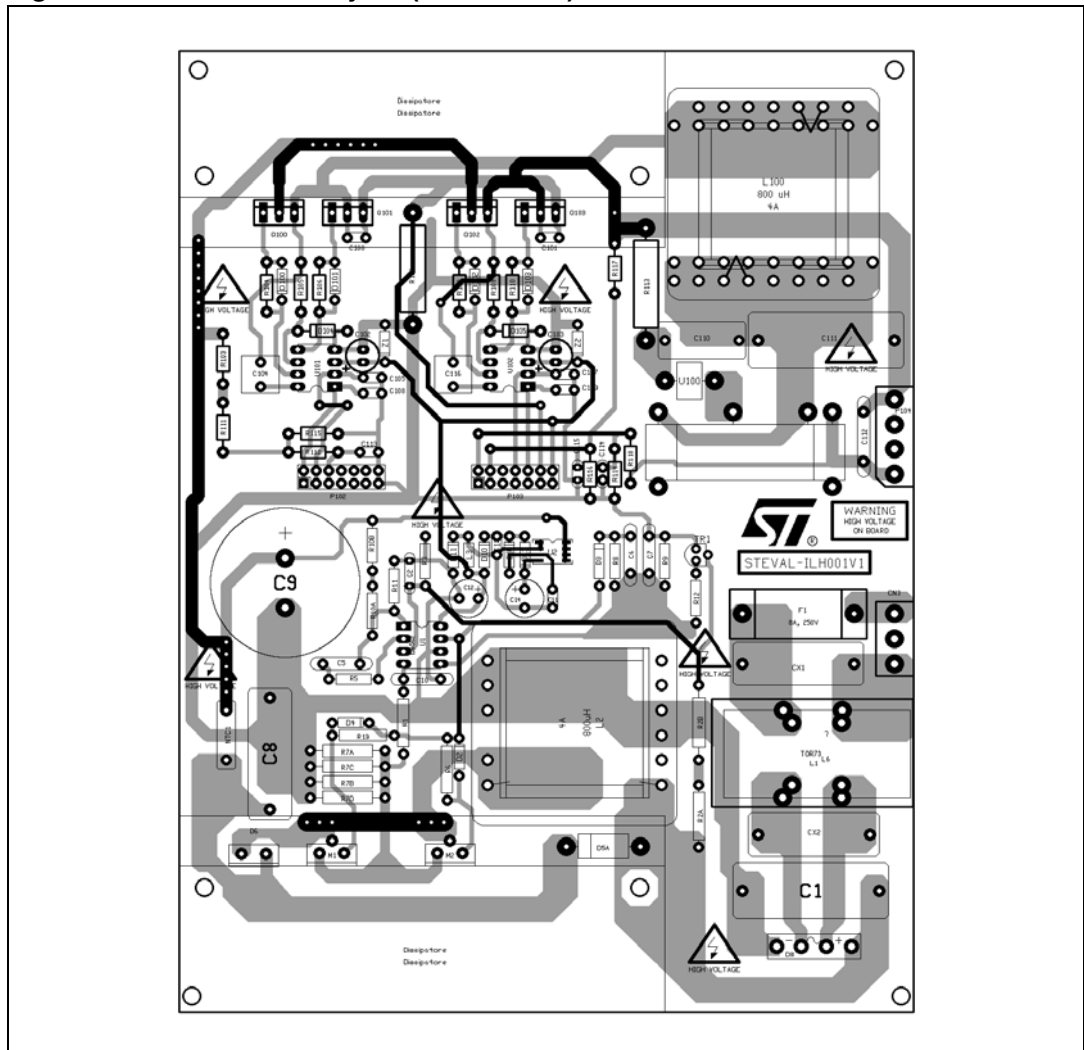
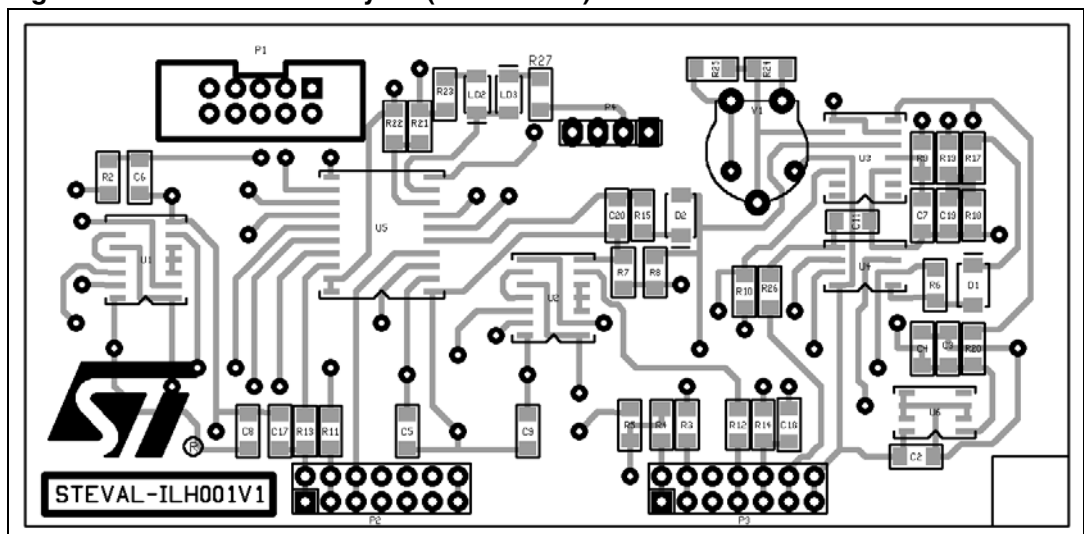


Figure 15. Control board layout (not to scale)



3.2 Bill of material

Table 1. PFC bill of material

Name	Value	Rated	Type
C1	1 μ F	400 V	polyester capacitor
C2	10 nF	50 V	ceramic
C5	1 μ F	50 V	ceramic
C6	330 pF	50 V	ceramic
C7	560 pF	50 V	ceramic
C8	470 nF	630 V	EPCOS B32523Q8474K
C9	220 μ F	450 V	EPCOS electrolytic capacitor B43504-B5227-M7
C10	330 pF	50 V	ceramic
C11	22 nF	50 V	ceramic
C12	47 μ F	35 V	Electrolytic
C13	100 nF	50 V	ceramic
C14	10 μ F	50 V	Electrolytic
CX1, CX2	330 nF	275 V	EPCOS X2 capacitor B32922A2334K
D2, D3, D4, D13	200 mA	100 V	Signal diode
D5A	3 A, 600 V		General purpose rectifier
D6	STTH8R06DIRG		STMicroelectronics
D8	8 A 1000 V		Bridge rectifiers
D9	Zener diode	15 V 1/2 W	
D10	STTH1L06	1 A, 600 V	STMicroelectronics
D11	STTH1L06	1 A, 600 V	STMicroelectronics
D13	1N4148		
F1	FUSE	250 V 8 A	
L1	2 x 6.8 mH	4 A 250 V	EPCOS Common mode chokes B82725-J2402-N20
L2	550 μ H 4 A		Magnetica part number 1555.0009
L3	2.2 mH		
M1,M2	STF12NM50N		STMicroelectronics
NTC1	S237		EPCOS B57237S0259M
R1	330 Ω	1% 1/4 W	
R2A R2B	680 k Ω	1% 1/4 W	
R3	10 k Ω	1% 1/4 W	

Table 1. PFC bill of material (continued)

Name	Value	Rated	Type
R5	6.8 k Ω	1% 1/4 W	
R6	6.8 Ω	1% 1/4 W	
R7A,R7B,R7C,R7D	0.68 Ω	1% 1/4 W	
R8	1.5 k Ω	1% 1/4 W	
R9	12 k Ω	1% 1/4 W	
R10A	470 k Ω	1% 1/4 W	
R10B	560 k Ω	1% 1/4 W	
R11	6.8 k Ω	1% 1/4W	
R12	12 k Ω	1% 1/4 W	
R13	6.8 Ω	1% 1/4 W	
TR1	BC557		TO92
U1	L6562		STMicroelectronics
U2	VIPer12AS-E		STMicroelectronics

Table 2. Full bridge bill of material

Name	Value	Rated	Type
C100,C101	100 pF	630 V	
C102, C103	10 μ F	25 V	
C104, C106	3.3 μ F	50 V	EPCOS polyester capacitor B32529-D5335-K000
C105, C107	33 pF	50 V	ceramic
C108,C109	68 pF	50 V	ceramic
C110	100 nF	400 V	EPCOS B32652A6104K
C111	680 nF	630 V	EPCOS B32523Q8684K
C112	220 pF	6 KV	Murata DECB33J221KC4B
C113,C114,C115	68 pF	50 V	ceramic
D100,D101,D102,D103	200 mA	100 V	Signal diode
D104,D105	STTH1L06		STMicroelectronics
L100	800 μ H	3.5 A	Magnetica part number 1775.0001, VOGT: SL0607112101
Q100,Q102	STP20NM50FD		STMicroelectronics
Q101, Q104	STGF10NB60SD		STMicroelectronics
R102	470 m Ω	1% 2 W	
R103	820 k Ω	1% 1/4 W	
R104,R106,R108, R110	100 Ω	1% 1/4 W	

Table 2. Full bridge bill of material (continued)

Name	Value	Rated	Type
R105, R109	22 Ω	1% 1/4 W	
R111	820 k Ω	1% 1/4 W	
R112, R115	10 k Ω	1% 1/4 W	
R113	15 k Ω	3 W	
R114, R116	47 k Ω	1% 1/4 W	
R117, R118	1 M Ω	1% 1/4 W	
T100	High voltage Transformer	N1/N2=55/3	VOGT part number SL0607111102
U100	SPARK GAP	235 V	EPCOS B88069X4290T502
U101, U102	L6385		STMicroelectronics
Z1,Z2	Zener diode	16 V 1/2 W	

Table 3. Control board bill of material

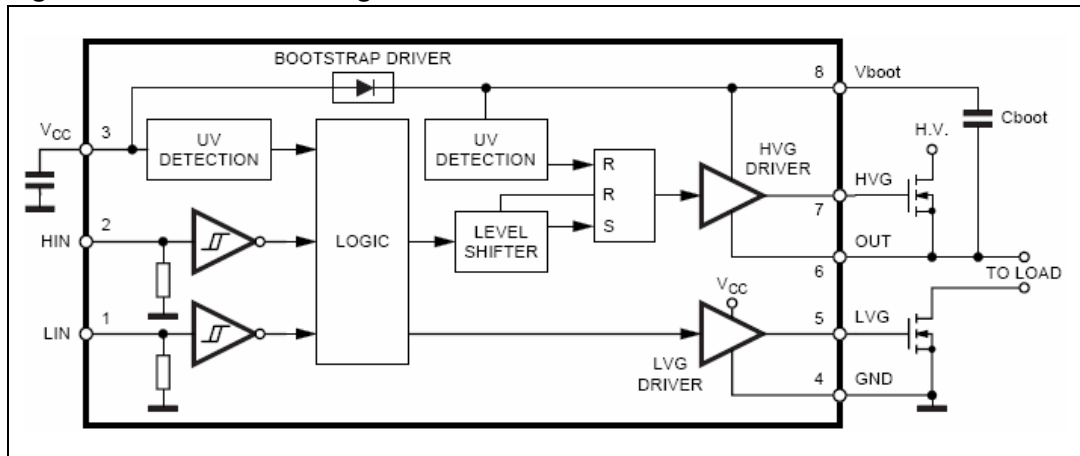
Name	POS	Rated	Type
C2	100 nF		SMD 1206
C3	10 μ F	15V	through hole
C4	100 nF		SMD 1206
C5,C8,C9	0.1 μ F		SMD 1206
C6	0.47 μ F		SMD 1206
C7	2.2 μ F		SMD 1206
C11	22 pF		SMD 1206
C17, C18	1 nF		SMD 1206
C19,C20	1 μ F		SMD 1206
D1,D2	BAT42		STMicroelectronics
LD2	Green LED		SMD 1206
LD3	Red LED		SMD 1206
R2	47 k Ω		SMD 1206
R5,R6	100 k Ω		SMD 1206
R7	5.6 k Ω		SMD 1206
R9	4.7 k Ω		SMD 1206
R10,R15,R20	1 k Ω		SMD 1206
R11,R12	10 Ω		SMD 1206
R3,R4,R8,R14,R17, R18,R19,R21,R22, R26	10 k Ω		SMD 1206
R23,R27	470 Ω		SMD 1206

Table 3. Control board bill of material (continued)

Name	POS	Rated	Type
R24			
R25			
U1,U2	74AC00		STMicroelectronics
U3	LM119		STMicroelectronics
U4	TS272		STMicroelectronics
U5	STF7LITE39B		STMicroelectronics
U6	LE50-CD	5 V 100 mA	STMicroelectronics
V1	100 k Ω		

4 L6385 high-voltage high and low side driver

Figure 16. L6385 block diagram



The L6385 is a high-voltage device, manufactured with BCD "OFF-LINE" technology. It has a driver structure that enables to drive independently referenced N-Channel Power MOSFETs or IGBTs. The upper (floating) section is enabled to work with voltage rail up to 600 V. The logic inputs are CMOS/TTL compatible for easy interfacing with controlling devices.

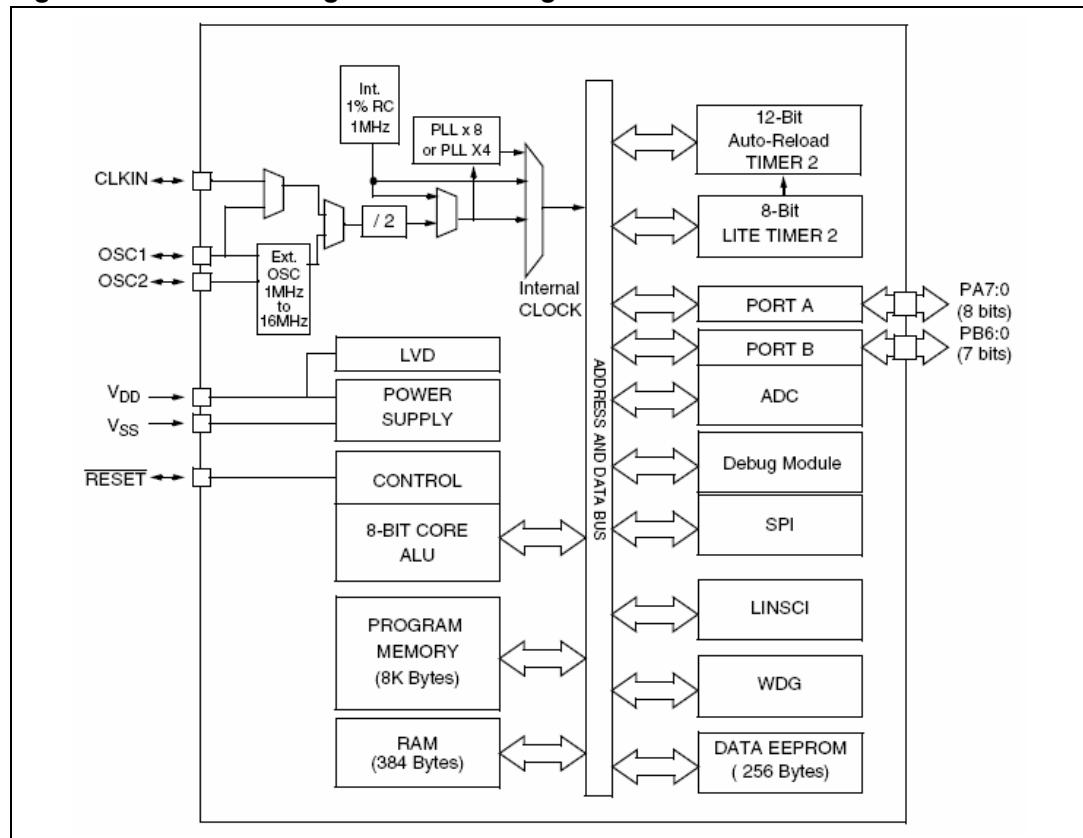
The main characteristic of this driver are:

- high-voltage rail up to 600 V
- dV/dt immunity ± 50 V/nsec in full temperature range
- driver current capability: 400 mA source, 650 mA sink
- switching times 50/30 nsec rise/fall
- with 1 nF load
- CMOS/TTL Schmitt trigger inputs with hysteresis and pull-down
- undervoltage lockout on lower and upper driving sections
- internal bootstrap diode
- outputs in phase with inputs

5 ST7LITE39 microcontroller

The ST7LITE3 is a member of the ST7 microcontroller family of products. All ST7s are based on a common 8-bit core, able to run up to 8 MHz clock frequency. Enhanced instructions like an 8x8-bit unsigned multiplication and indirect addressing allow good efficiency and a compact application code.

Figure 17. ST7FLIT3xB general block diagram

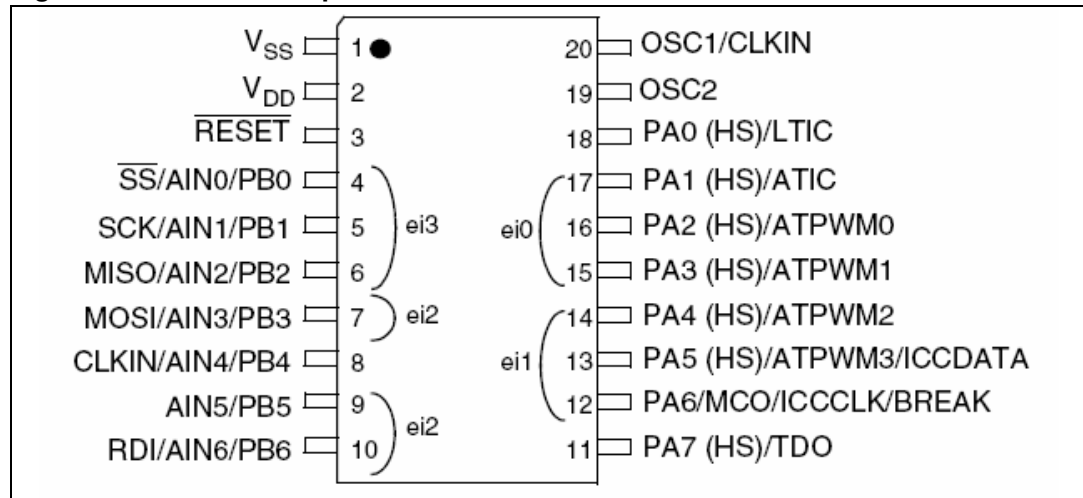


The MCU main characteristics are:

- internal RC oscillator with 1% precision at 8 MHz CPU frequency
- seven input channels 10-bit resolution A/D converter with 3.5 s of conversion time
- two 8-bit lite timers with prescaler
- two 12-bit auto-reload timers with 4 independent PWM outputs and programmable dead time generation
- 8 Kbytes flash program memory
- 384 bytes RAM
- 256 bytes data EEPROM
- SPI and SCI communication interfaces

Figure 18 shows the ST7FLITE39 pinout.

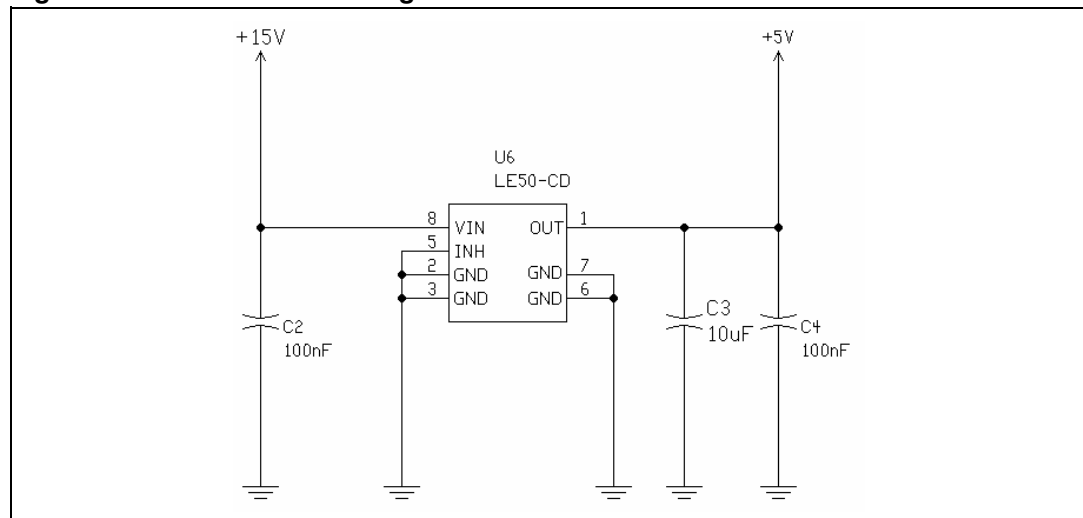
Figure 18. ST7FLITE39 pinout



5.1 Application pins

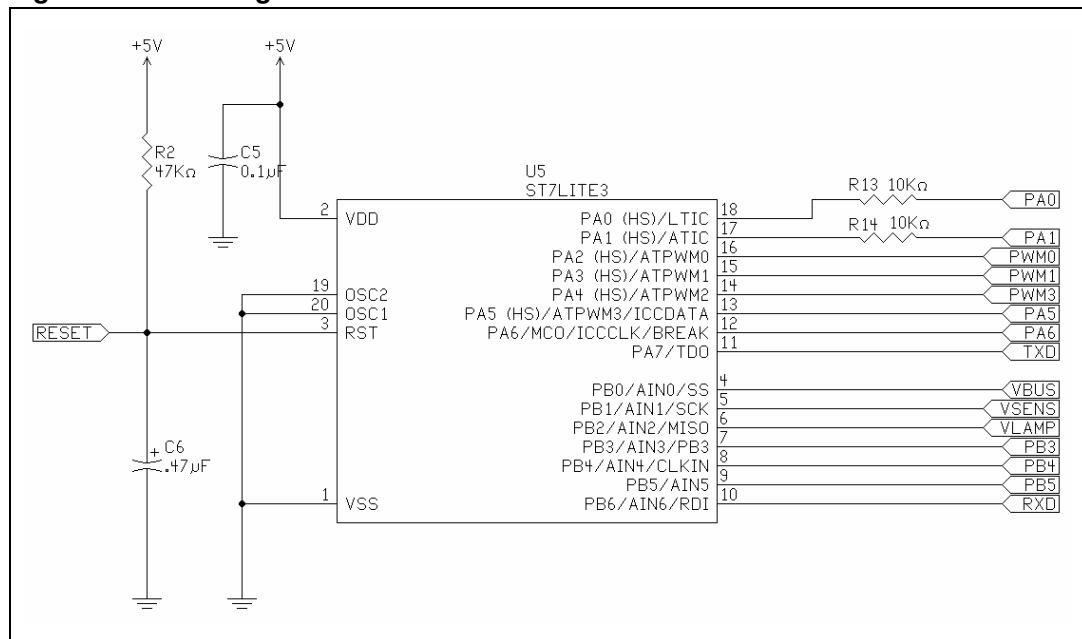
- Pin 1: GND
- Pin 2: VDD: main supply voltage. Power is supplied using an STMicroelectronics LE50 which is able to supply 5 V with $\pm 1\%$ tolerance. [Figure 19](#) shows the adopted circuit.

Figure 19. MU reference voltage circuit



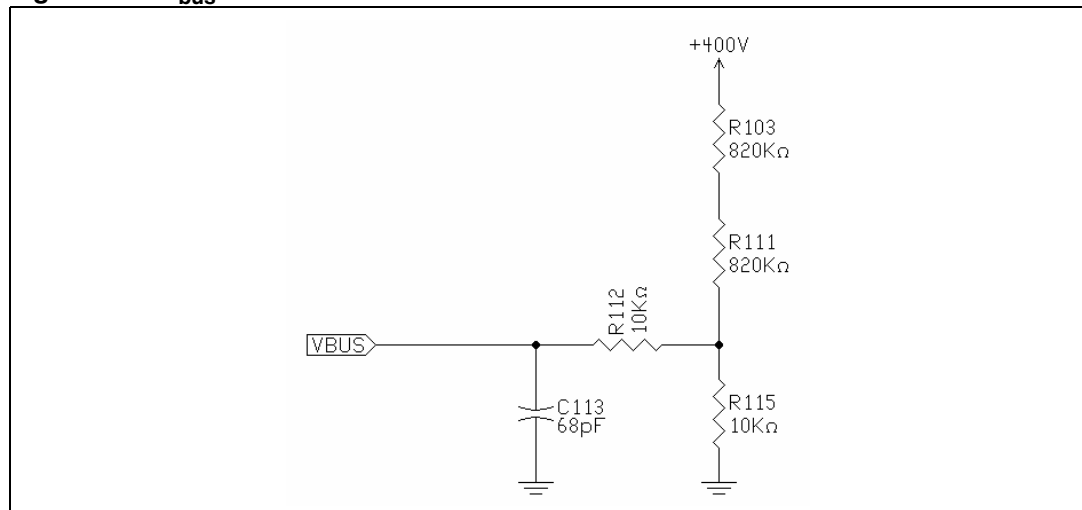
- Pin 3: reset pin

Figure 20. Pin usage and reset circuit

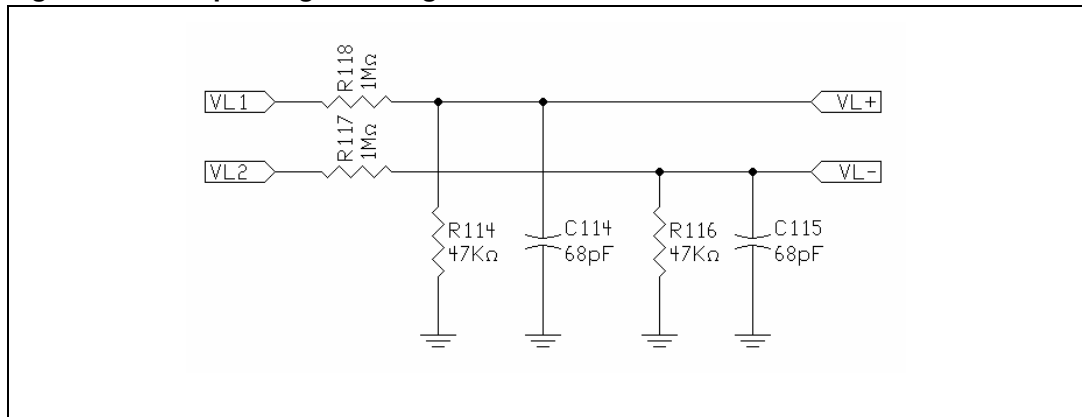
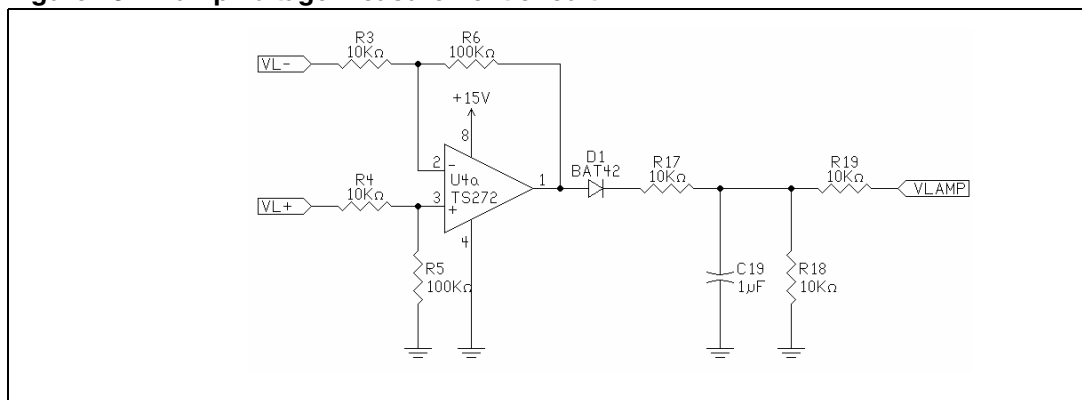


- Pin 4: ADC channel 0 analog input, to measure the main DC bus voltage (VBUS). A resistor partition is used to obtain, starting from a +400 V of bus a maximum of 5 V, compatible with the MCU voltage input, see [Figure 23](#).

Figure 21. V_{bus} measurement circuit



- Pin 5: ADC analog input 1: not used
- Pin 6: ADC analog input 2: This pin is used to measure the lamp voltage. In [Figure 23](#) there are two nets. The first one is a partitioning circuit composed of resistors R118-R114, the other one composed of R117-R116. The voltage across the capacitors C114 and C115 is used as input of U4a to obtain a signal compatible with the MCU input.

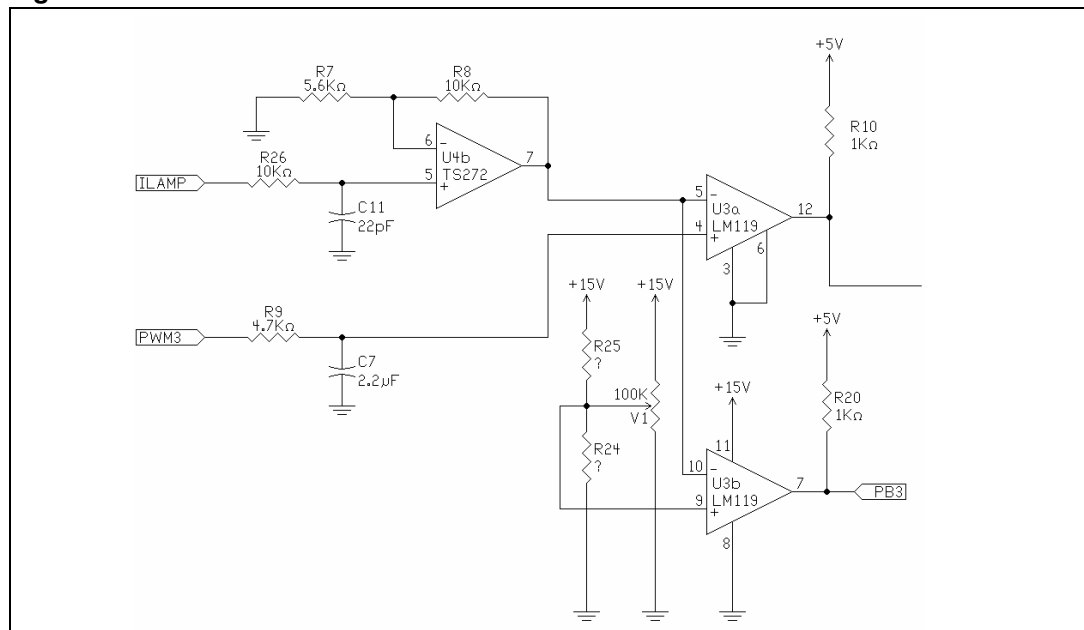
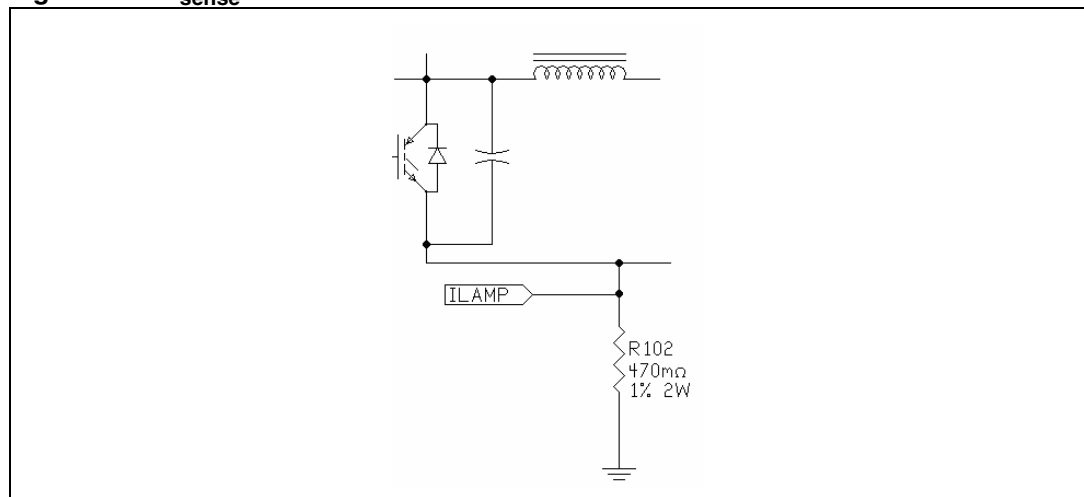
Figure 22. Lamp voltage sensing circuit**Figure 23. Lamp voltage measurement circuit**

- Pin 7: PB3 digital floating input with interrupt. This pin is used for maximum current protection.
- Pin 8: PB4 digital floating input. It is used for MCU V_{ref} calibration.
- Pin 9: push-pull output, used to drive two status leds. A green LED indicates the normal status. A red LED indicates a fault condition (for example overcurrent protection).
- Pin 10: SCI RXD, used for external communication, power line modem or PC
- Pin 11: SCI TXD, used for external communication, power line modem or PC
- Pin 12-13: PA6-PA5 not used
- Pin 14: PA4 output PWM3. It is used to generate a reference voltage for the constant current control.

The current signal is obtained through a sense resistor R102 (I_{LAMP} signal [Figure 25](#)). This voltage across R102 is amplified by U4b STMicroelectronics amplifier TS272 and it is compared using the comparator LM119 with the reference voltage coming from the MCU.

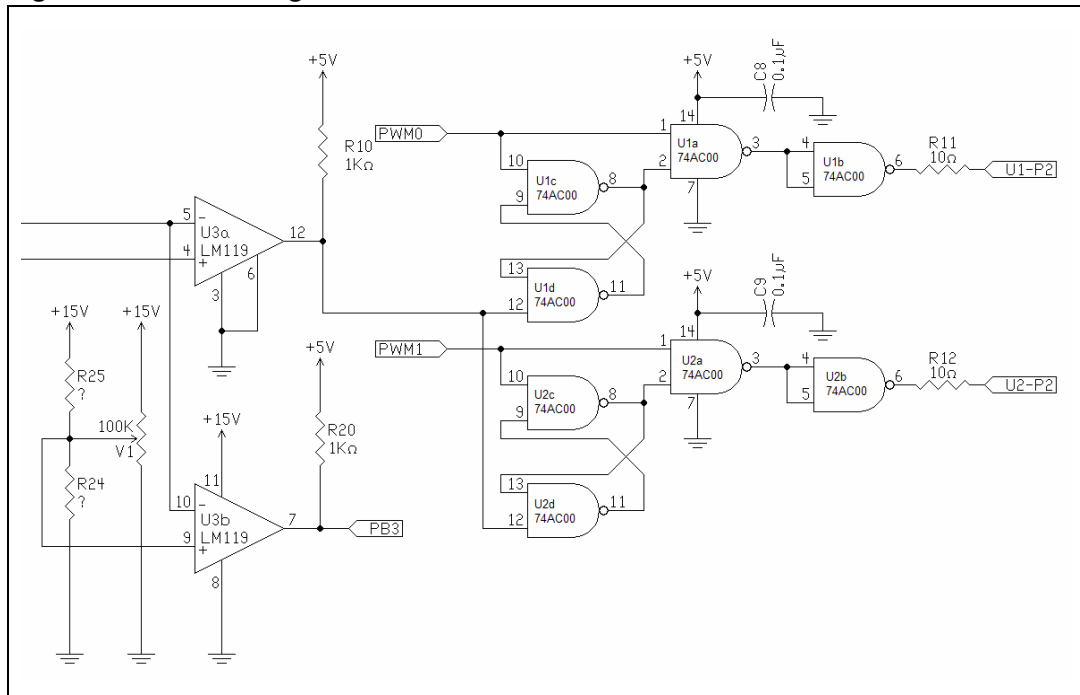
When the I_{lamp} signal exceeds the defined threshold, the comparator output falls, giving the reset signal to the drivers.

Figure 24. Constant current control

Figure 25. R_{sense} circuit

- Pin 15-16: PA3-PA2 output PWM1 and PWM0. These signals are connected to two flip-flops realized using U1 and U2. These flip-flops are used to obtain the drive signal for the high side switches, see [Figure 25](#). The set signal is obtained by PWM rising edge, directly from the signal PWM1 and PWM0. This signal is generated at 40 kHz fixed frequency. The reset signal is obtained by the output comparator U3. In this way it is possible to generate a PWM signal for drivers with fixed frequency and controlled duty cycle. Since the system works in continuous conduction mode to avoid instability in the current control circuit, the maximum duty cycle is limited at 50%.

Figure 26. Current regulation circuit



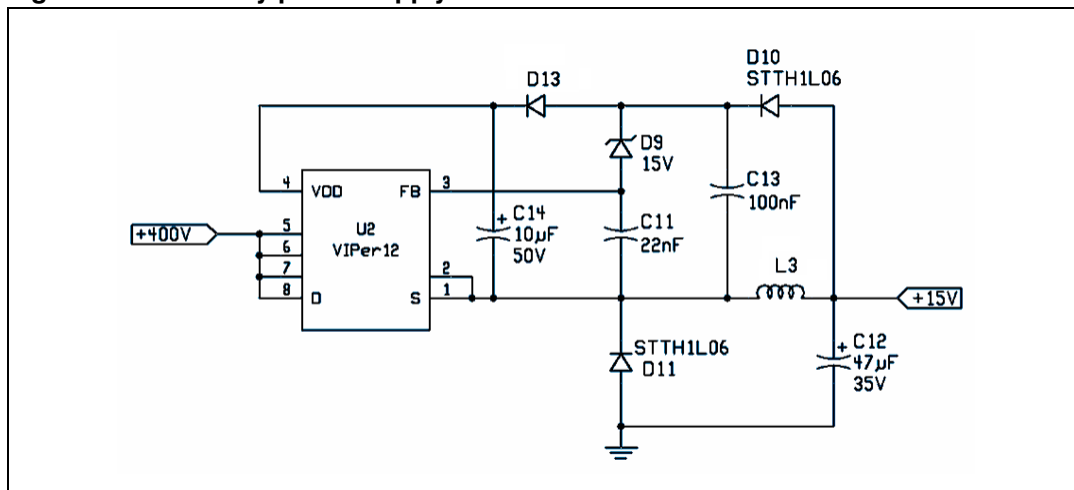
- Pin 17-18: PA1-PA0 push-pull outputs. These generate the signals for the low side driver. They are directly connected to the L6385 low_side_input pins.
- Pin 19-20: OSC2-OSC1 External quartz input: not used.

6 Auxiliary power supply

The proposed power supply can be successfully applied in applications requiring 15 V for the power switch gate driver. This circuit assures good performance in terms of size and performance at very low cost.

It is based on the VIPer12A-E in nonisolated buck configuration. [Figure 27](#) shows the schematic.

Figure 27. Auxiliary power supply

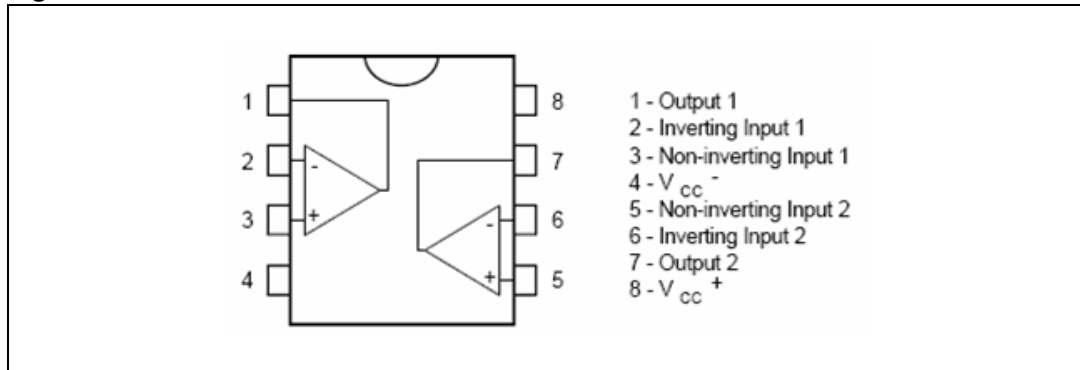


The VIPer12A-E is a low-cost smart power device with an integrated PWM controller that is suitable for such applications.

7 TS272 high-performance CMOS dual operational amplifiers

The TS272 devices are low cost, dual operational amplifiers designed to operate with single or dual supplies. These operational amplifiers use the ST silicon gate CMOS process allowing an excellent consumption-speed ratio. These series are ideally suited for low-consumption applications.

Figure 28. Pinout



The main characteristics of this device are:

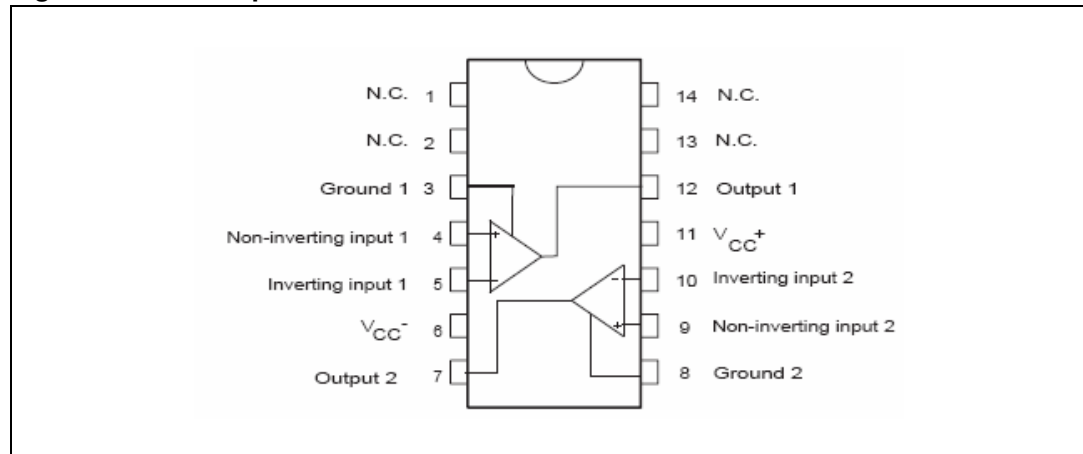
- output voltage can swing to ground
- excellent phase margin on capacitive loads
- gain bandwidth product: 3.5 MHz
- stable and low offset voltage
- three input offset voltage selections

8 LM119 high-speed dual comparators

These products are precision high-speed dual comparators designed to operate over a wide range of supply voltages down to a single 5 V logic supply and ground and have low input currents and high gains.

Although designed primarily for applications requiring operation from digital logic supplies, the comparators are fully specified for power supplies up to ± 15 V.

Figure 29. LM119 pinout



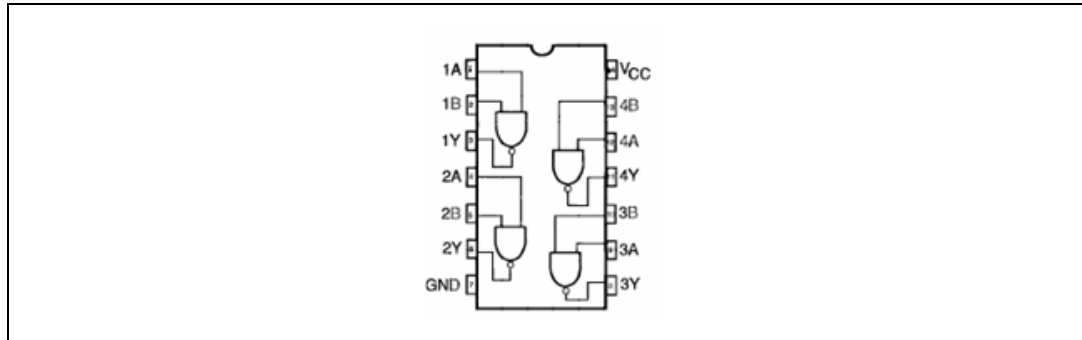
The main characteristics of this device are:

- two independent comparators
- supply voltage: +5 V to ± 15 V
- typically 80 ns response time at ± 15 V
- minimum fan-out of 2 on each side
- maximum input current of 1 μ A over operating temperature range
- inputs and outputs can be isolated from system ground
- high common-mode slew rate

9 74AC00 QUAD2-input NAND gates

The 74AC00 is an advanced high-speed CMOS QUAD 2-INPUT NAND gate fabricated with sub-micron silicon gate and double-layer metal wiring C2MOS technology. The internal circuit is composed of 3 stages including buffer output, which enables high noise immunity and stable output. All inputs and outputs are equipped with protection circuits against static discharge, giving them 2 KV ESD immunity and transient excess voltage. [Figure 30](#) shows the device pinout.

Figure 30. 74AC00 pinout



The main characteristics are:

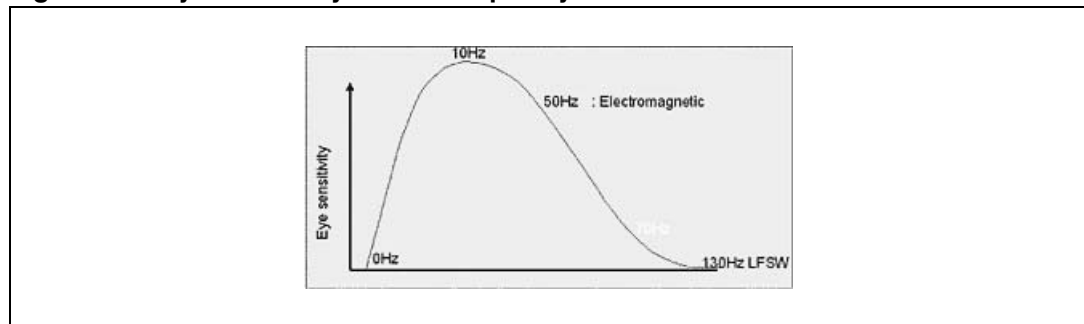
- high speed: $t_{PD} = 4 \text{ ns}$ (Typ.) at $V_{CC} = 5 \text{ V}$
- low-power dissipation: $I_{CC} = 2 \text{ mA}$ (max) at $T_A = 25 \text{ }^{\circ}\text{C}$
- high noise immunity: $V_{NIH} = V_{NIL} = 28 \% V_{CC}$ (min.)
- 50 W transmission line driving capability
- symmetrical output impedance: $I_{OHI} = I_{OL} = 24 \text{ mA}$ (min.)
- balanced propagation delays: t_{PLH} at t_{PHL}
- operating voltage range: $V_{CC} \text{ (OPR)} = 2 \text{ V to } 6 \text{ V}$
- pin and function compatible with 74 series 00
- improved latch-up immunity

10 Lamp data

The lamp data are given below and each is valid for the corresponding operating phase.

- Ignition phase: The ignition voltage in case of a cold lamp is about 4-5 kV. The ignition voltage increases with lamp temperature. The ignition voltage in case of a hot re-strike can reach 25 kV. The circuit is not designed to supply this very high voltage pulse.
- Warm-up phase: During this phase a high warm-up current must be supplied (30% higher than nominal current) to prevent lamp turnoff. The lamp voltage increases gradually starting from a quarter of nominal lamp voltage up to the nominal value. The warm-up time is about 2 minutes. For a 250 W metal halide lamp a current of 3.2 amps is applied.
- Burn phase: The lamp is designed to be driven with a low frequency square wave AC current to avoid acoustic resonance of the electric arc. Acoustic resonance occurs approximately in the frequency domain: 1 kHz - 1 MHz. Some frequency ranges free of acoustic resonance exist. The commutating frequency of the full bridge should be limited to the domain: 50 Hz - 10 kHz to avoid any risk of acoustic resonance. In this application the commutating frequency of 160 Hz has been chosen. This frequency has been chosen in order to avoid a flickering effect. For frequencies higher than 130 Hz eye sensitivity is practically zero. In [Figure 31](#) a diagram of eye sensitivity is shown.

Figure 31. Eye sensitivity versus frequency



The nominal lamp voltage is approximately 100 V and the nominal lamp power is 250 W. The differential resistance of the lamp is small and negative. To obtain a stable operating point, impedance in series with the lamp is needed.

11 PFC section design criteria

For PFC design criteria see AN 1875.

12 Full bridge design criteria

The design of full bridge section involves the inductor (buck) component and device selection.

12.0.1 Inductor design

The design specs are:

1. lamp current
2. lamp ripple current
3. lamp voltage
4. lamp ripple voltage

The design steps are summarized below:

1. Fix the switching frequency f_s and consequently the period T_s also is fixed. This frequency for power application is in the range 20 kHz ÷ 100 kHz
2. Fix the duty cycle estimation δ as $\delta = \frac{V_{out}}{V_{input}} = \frac{V_{lamp}}{V_{bus}}$
3. Fix the current ripple in the inductor L
4. Calculate the inductance value using the relation:

Equation 9

$$L = \frac{V_{lamp} \cdot (1 - \delta) \cdot T_s}{\Delta I}$$

For the inductance calculation:

- $f_s = 40 \text{ kHz}$, $T_s = 25 \text{ s}$
- $V_{lamp} = 100 \text{ V}$
- $V_{bus} = 400 \text{ V}$
- $\delta = 0.25$
- $\Delta I = 2 \text{ A}$

Using these parameters the inductance value is 0.93 mH. For this project an inductance of 0.8 mH is used.

12.1 Filter capacitor

To calculate the capacitor value that is in parallel to the lamp, the max current lamp ripple must be considered. The lamp current ripple must be limited in order to avoid acoustic resonance. In this application the current ripple was fixed at $\Delta I_{lamp} \pm 5\%$ of nominal current

Equation 10

$$\Delta V_{lamp} = R_{lamp} \cdot \Delta I_{lamp}$$

where R_{lamp} can be obtained by the relation (in the hypothesis of linear value):

Equation 11

$$R_{lamp} = \frac{V_{lamp}^2}{P_{lamp}}$$

Substituting this relation in the previous relation it is possible to obtain V_{lamp} . The relation to calculate the output capacitor is:

Equation 12

$$C = \frac{\Delta I}{8 \cdot f_s \cdot \Delta V_{lamp}}$$

- ΔI = inductor current ripple = 2 A

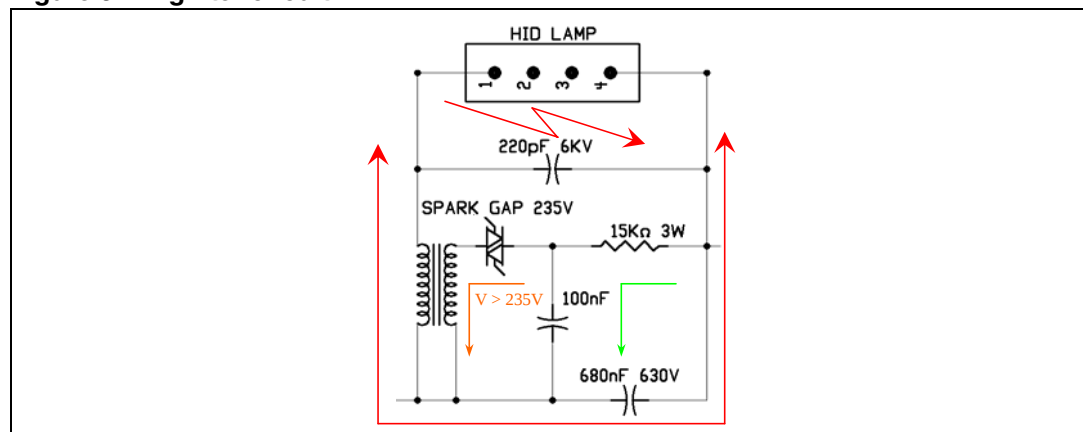
In this case we have:

- $I_{lamp} = 2.5$ A
- $\Delta I_{lamp} = \pm 5\% I_{lamp} = \pm 125$ mA = 250 mA
- $R_{lamp} = 40 \Omega$
- $\Delta V_{lamp} = 10$ V
- $C = 625$ nF. A capacitor of 680 nF 400 V was selected.

12.2 Igniter

For the design of the igniter the maximum ignition voltage must be considered. This ignition voltage is obtained by charging a capacitor (100 nF) using a resistor. When the voltage exceeds the gas spark gap threshold (235 V) capacitor is discharged in the primary winding of the high voltage transformer. This voltage is transferred at the secondary winding and a high voltage pulse is obtained, see [Figure 32](#).

Figure 32. Igniter circuit



12.3 Power MOSFET selection

For the selection of the Power MOSFET, the following rules must be considered:

- $V_{DSS} > V_{out}$
 - $I_D > I_{T(pk)}$
 - $V_{bus} = 400 \text{ V}$
 - $I_{T(peak)} = 4 \text{ A}$
- V_{DSS} greater than 20% of V_{bus} that is 480 V

The STP20NM50FD, FDmesh™ Power MOSFET was selected because it satisfies the following specifications:

- V_{DSS} : 500 V
- $R_{DS(on)}$: $< 0.25 \Omega$
- I_D : 20 A

This device was selected considering the losses in these devices which are composed of three parts: switch-on, conduction and switch-off losses.

The first loss is caused by the voltage across the MOSFET at switch-on, the second one depends on $R_{DS(on)}$ and RMS current, and the last one is caused by the current at switch-off.

The general formulas for conduction and switch-off losses are given below:

Equation 13

$$P_{cond} = I_{RMS}^2 \cdot R_{DS(on)} \cdot \delta$$

Equation 14

$$P_{turn-off} = V_{bus} \cdot I_{rms} \cdot t_{cross} \cdot f$$

12.4 IGBT selection

Considering the current level and the working frequency (160 Hz) the best choice for the low side device is the IGBT device. In parallel at this power switch the freewheeling diode works at high frequency in continuous conduction mode. Since the diode is stressed with high di/dt , T_{rr} , Q_{rr} , and I_{rms} became key parameters especially when power loss must be minimized. For both reasons the STGF10NB60SD is the right choice for this application. Using high voltage technology based on a patented strip layout, STMicroelectronics has designed an advanced family of IGBTs, the PowerMESH™ IGBTs, with outstanding performances. The suffix "S" identifies a family optimized with minimum on-voltage drop for low frequency applications ($< 1 \text{ kHz}$).

- V_{Ces} : 600 V
- $V_{cesat(max)}$: $< 1.8 \text{ V}$
- I_D : 10 A

Moreover in the same package a fast diode is integrated with the following characteristics:

- $T_{rr(typ)}$: 50 ns
- $Q_{rr(typ)}$: 70 nC

The power losses can be divided in two quantities: IGBT losses and diode losses. The IGBT power losses are mainly due to the conduction phase and depend on V_{cesat} .

Equation 15

$$P_{\text{IGBTcond}} = V_{\text{ce}} \cdot I_{\text{F(av)}}$$

In the diode the conduction losses (considering a duty cycle of 50%) can be estimated using the following formula:

Equation 16

$$P_{\text{Dcond}} = V_{\text{to}} \cdot I_{\text{F(av)}} + r_d \cdot I_{\text{F(rms)}}^2$$

Where:

- P_{Dcond} = diode conduction losses
- $I_{\text{F(av)}}$ = average forward current
- $I_{\text{F(rms)}}$ = RMS forward current

13 Experimental results

These results have been obtained at a rated input voltage of 230 V.

Ambient temperature: 23 °C.

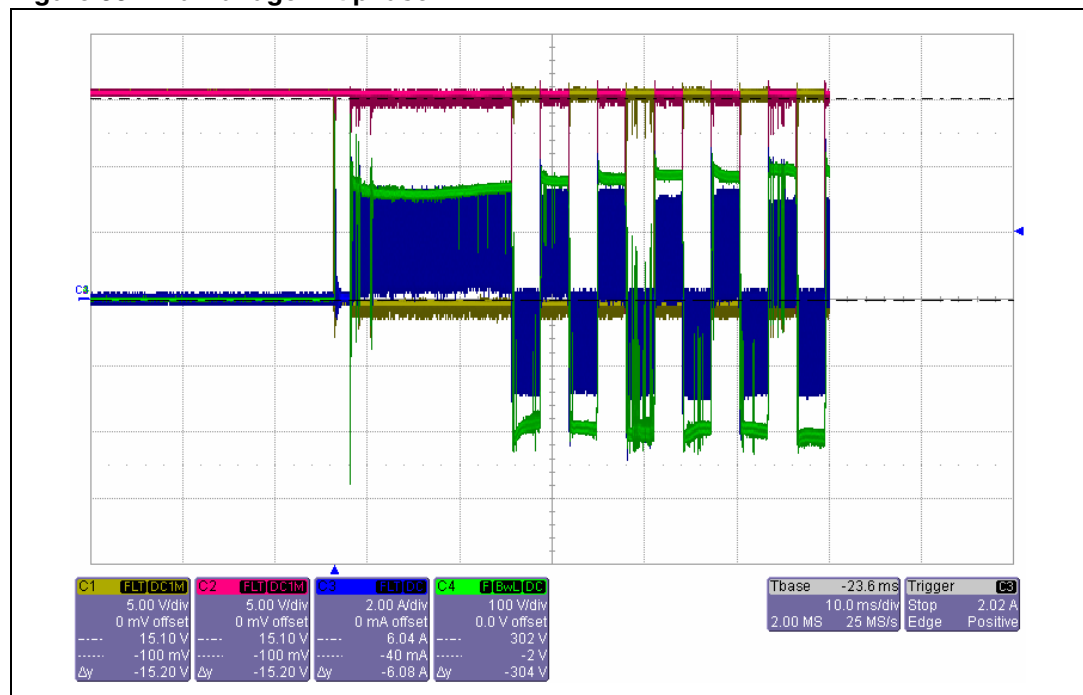
In the full bridge section the following phases have been analyzed:

1. init phase
2. ignition phase
3. warm-up phase
4. steady state phase

13.1 Init phase

During this phase the DC bus voltage is sensed and both low side devices are switched ON. In this way both bootstrap capacitors are charged. The init phase is shown below in [Figure 33](#).

Figure 33. Full bridge init phase

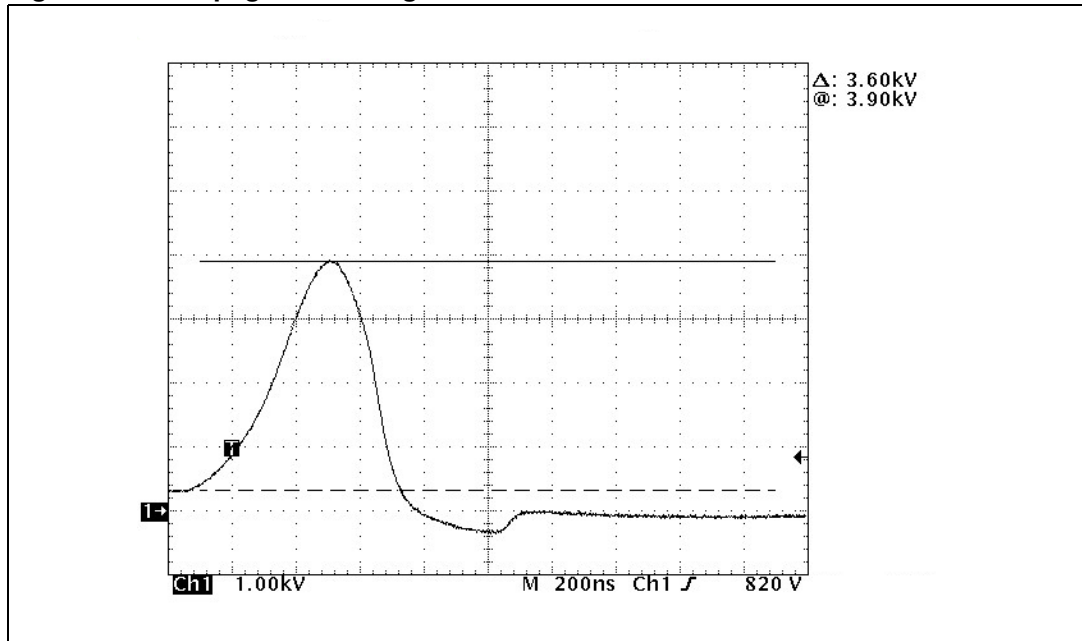


- C1 = low side IGBT 1 gate voltage
- C2 = low side IGBT 2 gate voltage
- C3 = inductor current
- C4 = lamp voltage

13.2 Lamp ignition phase

The high voltage transformer generates a proper ignition voltage to ignite the lamp. The voltage across the lamp is shown below in [Figure 34](#).

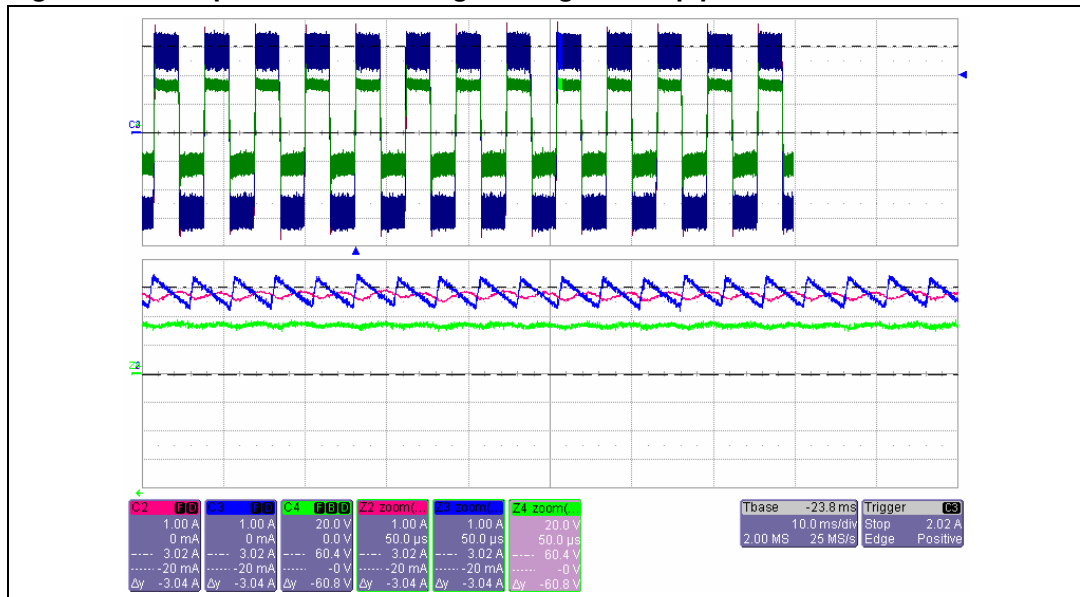
Figure 34. Lamp ignition voltage



13.3 Warm-up phase

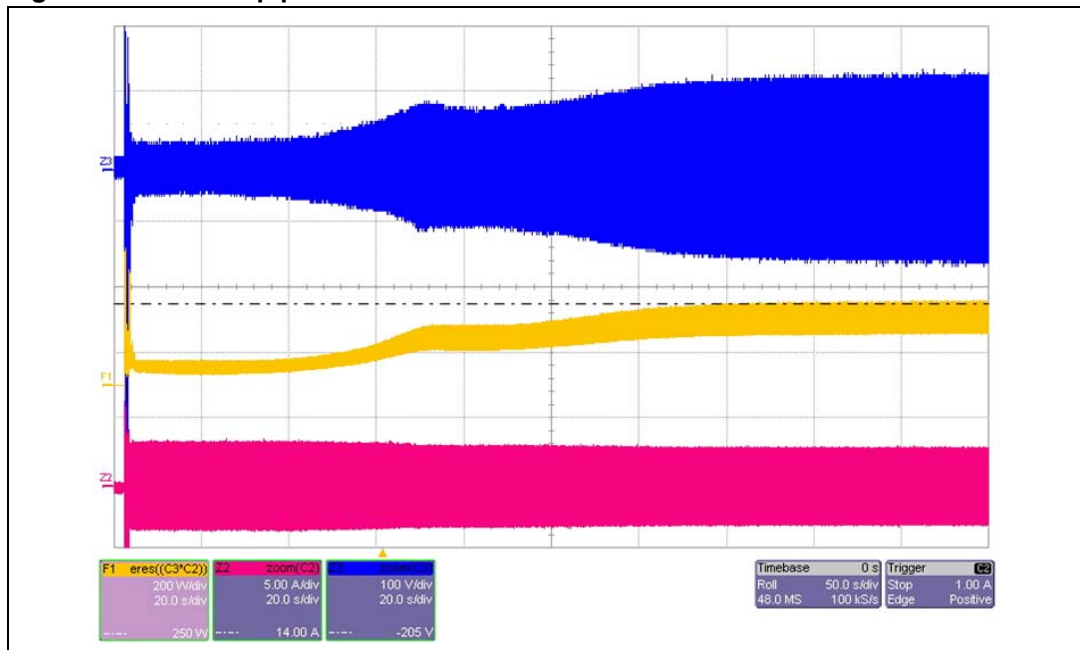
During this phase the lamp current is limited and the lamp voltage increases starting from a quarter of nominal voltage until the rated voltage. During this phase the lamp power increases and at 80% of nominal lamp power the control power is activated, regulating the lamp power.

Figure 35. Lamp current and voltage during warm-up phase



- C2 = lamp current
- C3 = inductor current
- C4 = lamp voltage

Figure 36. Warm-up phase



13.4 Burn phase

During this phase the lamp is supplied with low-frequency square wave current. The lamp current and the lamp power are maintained constant and some waveforms are shown in [Figure 37](#) and [38](#).

Figure 37. Steady state phase: lamp current, voltage and lamp power

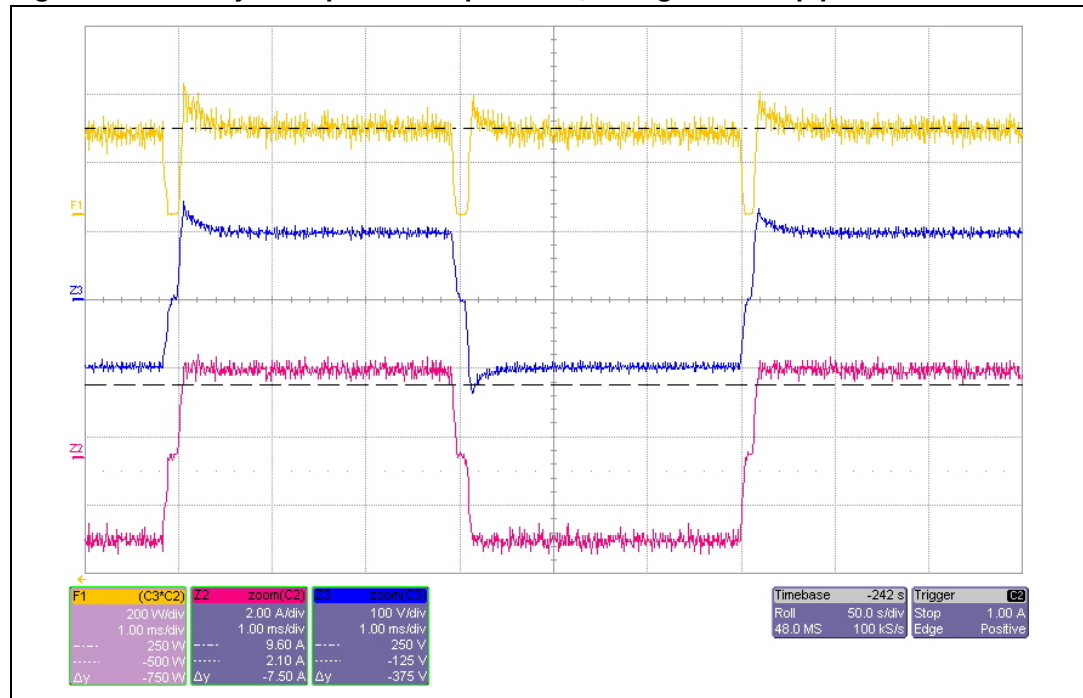
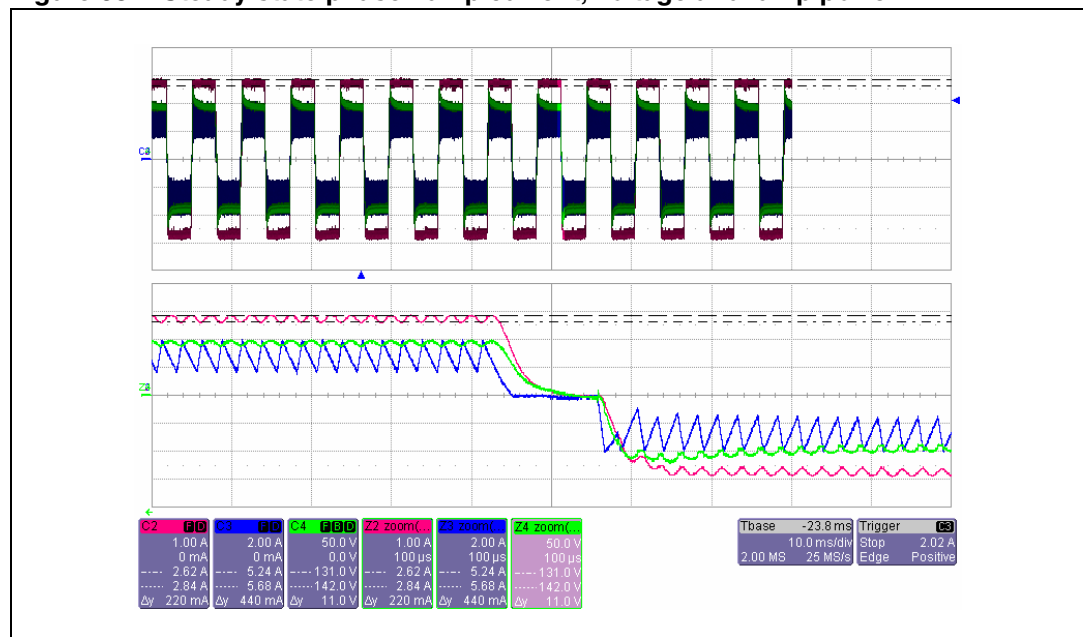


Figure 38. Steady state phase: lamp current, voltage and lamp power



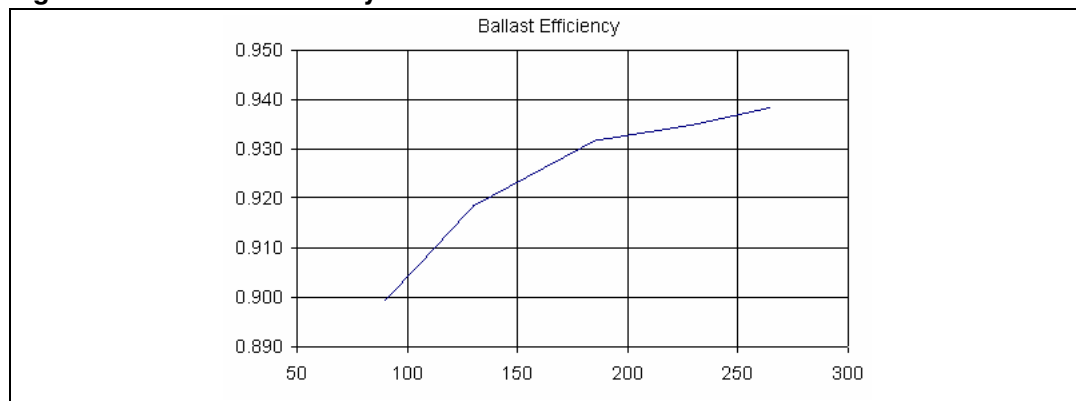
13.5 PFC run phase

During the run phase the input power the power factor and the input current THD have been measured. The results are given in [Table 4](#).

Table 4. Power factor and input current THD measurements

Vin (rms) V	Power factor	THD%
115	0.994	10
230	0.940	27

Below [Figure 39](#) shows a diagram of total ballast efficiency versus input voltage. The system efficiency is obtained as a ratio of lamp power to input power.

Figure 39. Ballast efficiency

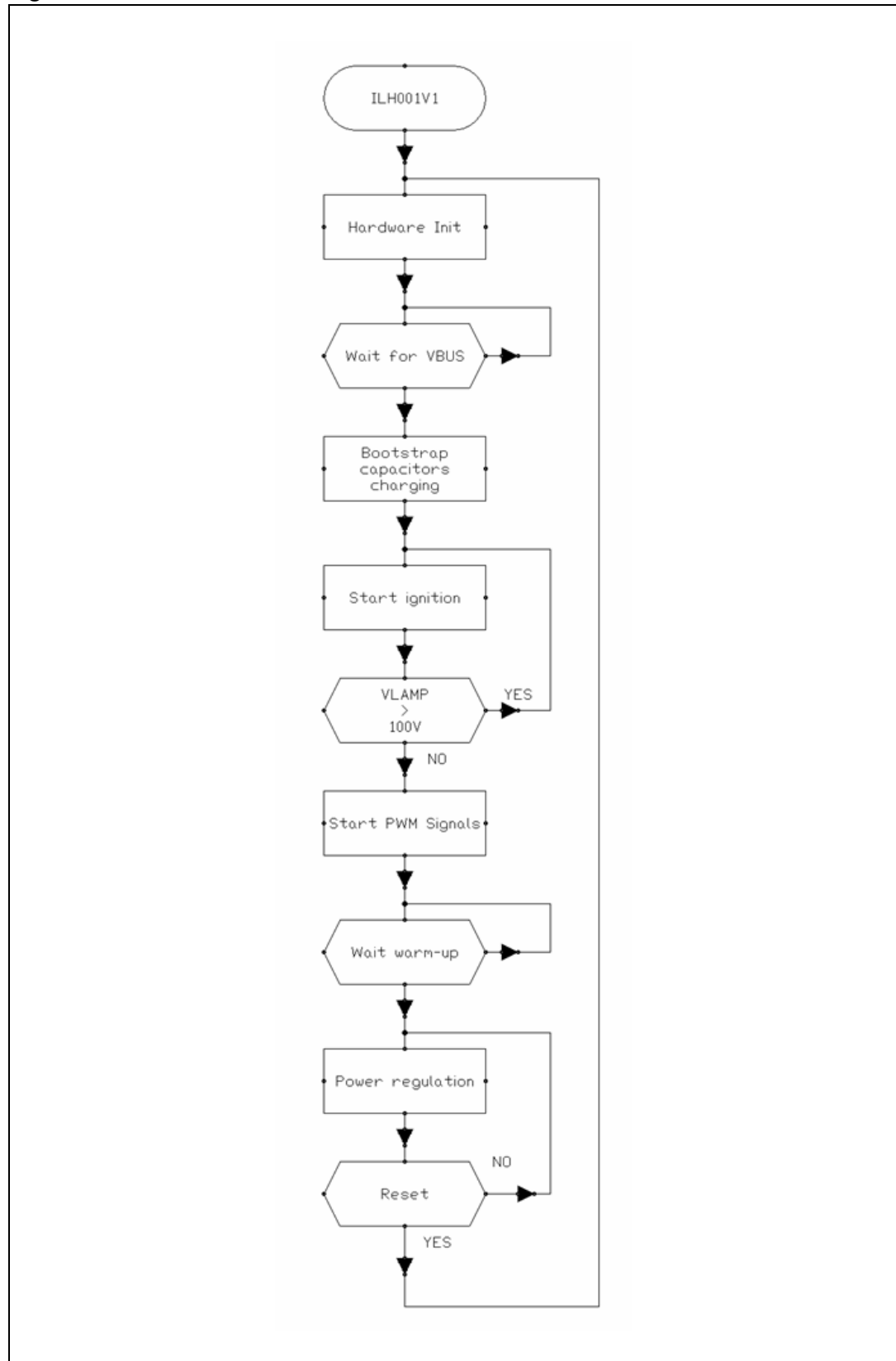
13.6 Thermal measurement

In the output stage a thermal measurement on the power device has been performed. On the devices a heat sink having thermal resistance $R_{th} = 3.23 \text{ }^{\circ}\text{C/W}$ has been mounted. The temperature was measured on the top of the packages of the power devices by means of a thermocouple. A ΔT of $55 \text{ }^{\circ}\text{C}$ above ambient temperature has been measured.

14 Firmware flowchart

A simplified firmware flowchart is given in [Figure 40](#).

Figure 40. Firmware flowchart



15 References

1. "Design of Fixed-Off-Time controlled PFC Preregulators with the L6562" (AN1792)
2. "EVAL6562-375W, 375 W Fot-Controlled PFC pre-regulator with the L6562 (AN1895)
3. "L6562-250W High performance TM PFC"
4. "L6562 Transition-Mode PFC Controller" (datasheet)
5. "STF12NM50 N-channel 500 V 0.29 Ω 11A MDMesh Power MOSFET" (datasheet)
6. "STTH8R06DT Turbo 2 ultrafast high voltage rectifier" (datasheet)
7. "L6385 HIGH-VOLTAGE HIGH AND LOW SIDE DRIVER" (datasheet)
8. "STF20NM50 N-channel 500 V 0.29 Ω 11A MDMesh Power MOSFET" (datasheet)
9. "STGP10NB60S N-channel 10 A 600 V PowerMesh IGBT" (datasheet)
10. "VIPer12 Low Power OFF-Line SMPS Primary Switcher" (datasheet)
11. "ST7FLITE39 8-bit MCU with single voltage Flash, data EEPROM, ADC, timers, SPI, LINSCI" (datasheet)
12. "74AC00 QUAD 2-INPUT NAND GATE" (datasheet)
13. "LM119 High speed dual comparators" (datasheet)
14. "TS272I HIGH PERFORMANCE CMOS DUAL OPERATIONAL AMPLIFIERS" (datasheet)
15. "LE50AB Very low drop voltage regulators with inhibit" (datasheet)

16 Revision history

Table 5. Document revision history

Date	Revision	Changes
06-May-2008	1	Initial release

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