AN2711
Application note

120 V_{AC} input-Triac dimmable LED driver based on the L6562A

Introduction

The cost of power LEDs is rapidly decreasing, while performance is improving. Their efficacy (light out per watt in) is now competitive with compact fluorescent lamps, while their life cycle is significantly longer at 100,000 full-power hours (11+ years) at half brightness.

Dimming LEDs can extend the life cycle further, and also reduce power drain. By far the most common dimming method is the Triac phase-control dimmer, which directly replaces the AC On-Off switch, but can be used only with incandescent lamps and specially designed fluorescent ballasts.

If the dimmer's thyristor current falls below its holding current, it stops conducting until it receives another pulse from the dimmer's triggering circuit. The power converter does not receive input power except for a very brief pulse each time the thyristor fires, until the thyristor turns off because of a lack of holding current. Performance of the converter is very erratic, and the LED load flickers badly.

This application note presents a low-cost driver for LEDs that is compatible with Triac phase-control dimmers. The design gives luminaire manufacturers a low-cost, commonly available dimming option for home fixtures. A side benefit is that, when not wired to a dimmer, the unit's power factor is over 0.9. The physical design can be made small enough to power a PAR38 lamp having 65 W equivalent illumination.

The design is based on the ST L6562A transition-mode PFC controller driving a single stage PFC-flyback power converter.

The device features extremely low consumption (60 µA max. before startup and <5 mA operating) and includes a disable function suitable for IC remote on/off, which makes it easier to comply with energy saving requirements (Blue Angel, ENERGY STAR®, Energy2000, etc.).

The L6562A's totem-pole output stage, capable of a 600 mA source and an 800 mA sink current, is suitable for driving high current MOSFETs or IGBTs.

Contents

1 **Background 6**

1.1 Characteristics of the Triac-based dimmer 6

1.2 Damping circuits 8

2 **Other input filter effects 10**

2.1 Line impedance affects input filter damping 10

2.1.1 Control and reduce the line impedance range 10

2.1.2 Discrete inductor 10

2.1.3 Common-mode choke differential L 10

2.1.4 How to measure leakage inductance 10

2.1.5 Coil separation 10

2.2 Powering the control circuits 11

3 **Filtering the LED current - electrolytic capacitors revisited 13**

3.1 Strobe effects 13

3.2 Benefits of electrolytic filters 13

3.2.1 Reduced crest factor in LEDs 13

3.2.2 Better regulation of housekeeping voltages 13

3.3 Electrolytic life calculations 13

3.4 Selecting the filter capacitors 14

3.4.1 LED slope resistance (dynamic impedance) 14

3.4.2 Capacitor values 14

3.5 Feedback loop characteristics 14

3.6 Regulating the LED current 14

3.7 Acoustic noise 15

4 **Hardware design of the STEVAL-ILL016V2 demonstration board . . . 16**

5 **Circuit description 18**

6 **Performance 20**

6.1 Undimmed performance 20

6.1.1 Setup for minimum dimmable output 20

6.1.2 Setup for greatest voltage stresses 21
6.1.3 Setup for maximum power 22
6.1.4 Setup for maximum output current 23
6.2 Dimmed performance 25
6.3 Startup time 26
6.3.1 Dimmed start issue 27
6.4 Conducted EMI 27

7 BOM list 29

8 PC layout 32

9 References 33

10 Revision history 35

List of tables

Table 1. Jumper and capacitor selection table . . . 19
Table 2. Current set resistor selection . . . 19
Table 3. Performance at 9 W into 8 series LEDs . . . 20
Table 4. 12 W into 11 series LEDs . . . 21
Table 5. Performance at 16 W into 10 series LEDs . . . 23
Table 6. Performance at 16 W into 5 series LEDs . . . 24
Table 7. Undimmed temperatures, configured as above (worst case), 120 V input . . . 24
Table 8. Temperatures, unit dimmed to maximum input power, 120 V in(~22.4 W, worst case) . . . 26
Table 9. BOM list . . . 29
Table 10. Document revision history . . . 35

List of figures

Figure 1. Thyristor dimmer with incandescent light . . . 6
Figure 2. Non-dimmable power converter LED driver . . . 7
Figure 3. Line voltage (yellow) and line current (green) into the unloaded EMI filter . . . 8
Figure 4. Thyristor current due to L-C ringing . . . 8
Figure 5. Adding a damper to the EMI filter . . . 9
Figure 6. Polarized damper . . . 9
Figure 7. Schematic of normal bootstrap supply . . . 11
Figure 8. Schematic of regulated housekeeping supply . . . 12
Figure 9. LED current vs average input voltage, showing regulation takeover . . . 15
Figure 10. Image of PC board . . . 16
Figure 11. Schematic diagram . . . 17
Figure 12. 96 V input voltage 9 W, 8 series LEDs . . . 20
Figure 13. 132 V input voltage 9 W, 8 series LEDs . . . 20
Figure 14. 96 V input voltage . . . 21
Figure 15. 132 V input voltage . . . 21
Figure 16. Stress on FET and diode . . . 22
Figure 17. 96 V line 16 W, 10 series LEDs . . . 23
Figure 18. 132 V line 16 W, 10 series LEDs . . . 23
Figure 19. 96 V input 16 W, 5 series LEDs . . . 24
Figure 20. 132 V input 16 W, 5 series LEDs . . . 24
Figure 21. Dimmer at maximum output . . . 25
Figure 22. Detail of line current (magenta = 0.5 A/div) . . . 25
Figure 23. Dimmer at 90 degrees . . . 25
Figure 24. Detail of line current (magenta = 0.5 A/div) . . . 25
Figure 25. Dimmer at 90 degrees . . . 26
Figure 26. Detail of line current (magenta = 0.5 A/div) . . . 26
Figure 27. Time from power in to light out . . . 27
Figure 28. Conducted EMI . . . 28
Figure 29. Transformer detail . . . 31
Figure 30. Top . . . 32
Figure 31. Bottom . . . 32

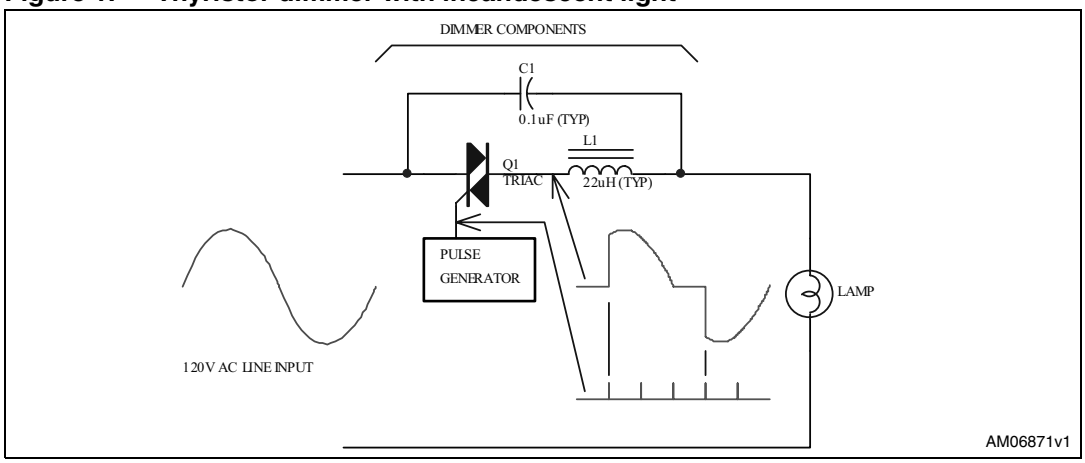
1 Background

1.1 Characteristics of the Triac-based dimmer

Conventional “2-wire” dimmers replace wall switches in M. It is highly desirable to have the LED driver accept power from a Triac-dimmed source.

The Triac dimmer reduces load power by delaying the application of load voltage during each half cycle. The scheme works very well for resistive loads such as incandescent lamps, but less so for other load types.

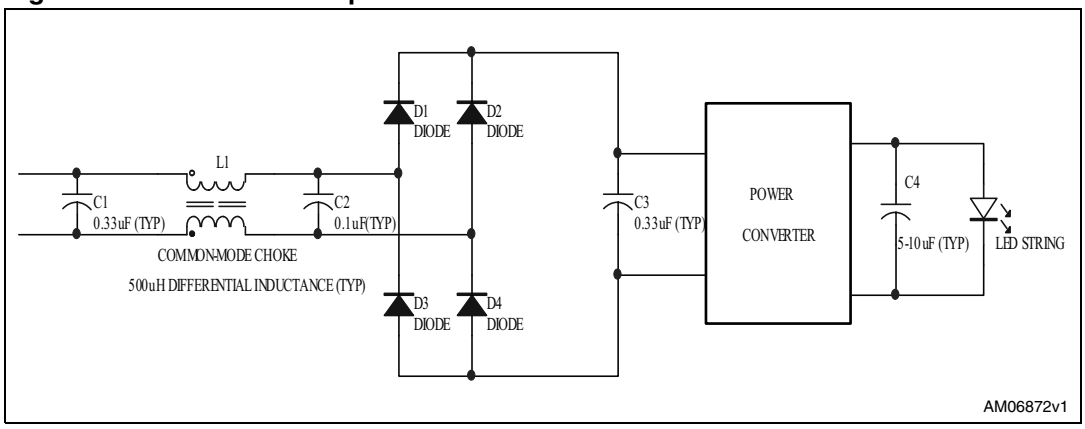
Figure 1. Thyristor dimmer with incandescent light



The thyristor turns on abruptly when the pulse generator fires, and it turns off near the voltage zero crossing when current falls below its holding current. The inductor and capacitor filter the sharp voltage edge to reduce conducted EMI. The lamp provides resistive damping to the L-C filter, and its resistance provides holding current to the thyristor. While the Triac is turned off, the lamp's low impedance causes nearly the entire line voltage to appear across the dimmer circuit, providing a clean reference signal from the voltage zero crossing until the Triac fires.

When the thyristor feeds an electronic load, such as a power converter, the damping and holding current effects of the lamp load are not present. Typically, the electronic load has an input EMI filter and a small capacitor to provide steady voltage for the power converter. No damping is present.

Figure 2. Non-dimmable power converter LED driver



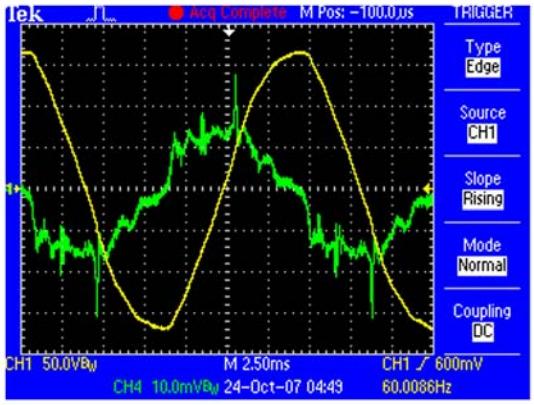
Many fluorescent, compact fluorescent, and LED drivers have warnings stating “not for use with dimmers” because they are unable to cope with the sudden rise of voltage late in the half cycle, or the reduced average voltage. Many low-cost drivers directly rectify the incoming AC and apply the resulting pulsed DC to capacitive filters. Current is drawn from the source during a very short period at the peak of the incoming voltage waveform, and no current is drawn during the remainder of each half cycle.

The Triac requires a minimum holding current, typically 30 to 50 mA, during the entire half cycle. If the current falls below that level, or if it reverses, the Triac turns off. It may or may not fire again during that half cycle, and an unknown voltage is left on the dimmer's timing capacitor for the next half cycle. Chaotic operation results if the holding current is not maintained.

Switchmode lamp drivers of any kind must include EMI filters at their AC inputs. In addition, the Triac dimmer may (and should) contain its own L-C filter, and the AC line is slightly inductive. All the filters typically contain only inductive and capacitive components - the sharply increasing input voltage, when the Triac fires each half cycle, causes current ringing which reverses several times during the half cycle. The Triac may continue to conduct during brief reversals (microseconds to tens of microseconds), or it may turn off. The variable voltage step and variable timing can cause the gating circuit to apply triggers to the Triac at random times, leading to flickering in the lamp.

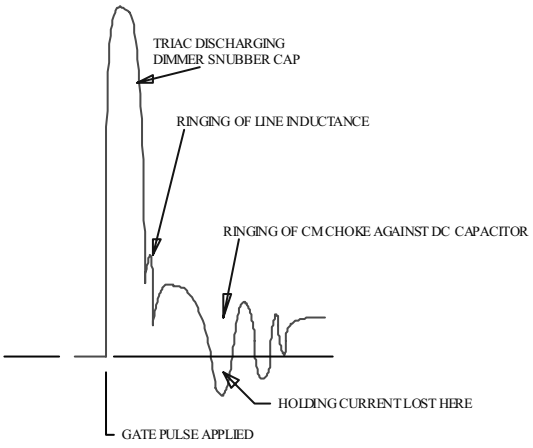
Current drawn by a capacitive EMI filter varies considerably, even without the Triac dimmer. At low power levels (around 15 W) the current drawn by the EMI filter is a significant portion of the total current. It must be taken into account in the design. The incoming AC voltage waveform is distorted by other loads - its slope varies from the smooth sine wave one would expect. Typically, there is a notch at the top of the waveform, caused by rectifiers on other equipment which draws current, followed by a flat top caused by capacitive loads drawing current through rectifiers, followed by a step downward as the rectifiers go through reverse recovery (abruptly ceasing to draw reverse current). The rapid downward slope can cause a capacitive load such as the EMI filter input to supply reverse current through the Triac to the source. Input current (Triac holding current) is sharply reduced or reversed. The current is out of phase with the voltage between the voltage peaks and the voltage zero crossings. The filter supplies some of the load current during these intervals, stealing holding current from the Triac.

Figure 3. Line voltage (yellow) and line current (green) into the unloaded EMI filter



With the dimmer phased back, when the Triac fires the current rings repeatedly through zero, and the holding current comes and goes. The thyristor may turn off until it is again triggered by the pulse generator.

Figure 4. Thyristor current due to L-C ringing

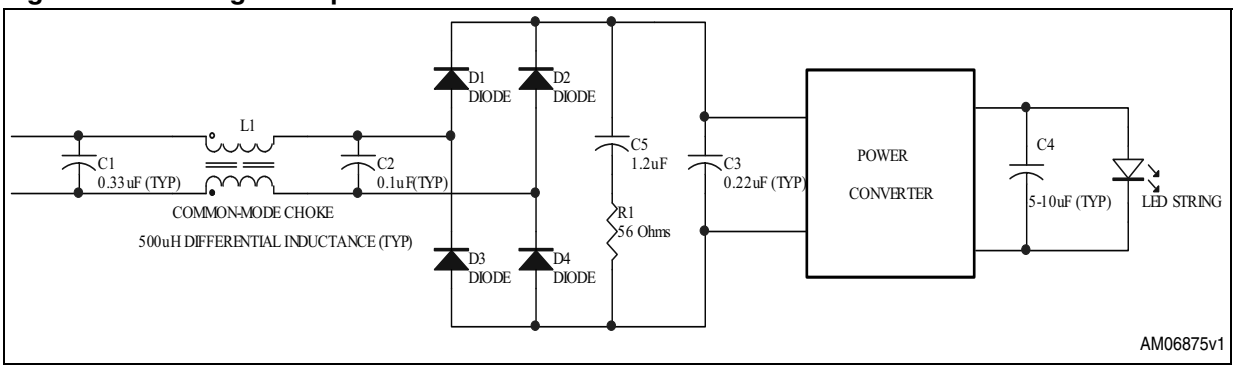


1.2 Damping circuits

If the Triac is to remain in control, current reversals between triggering and the voltage zero crossing must be eliminated. STMicroelectronics has developed a way to do this without violating existing patents, and a patent for this technique has been applied for. The patent is licensed to anyone using ST semiconductors at no charge.

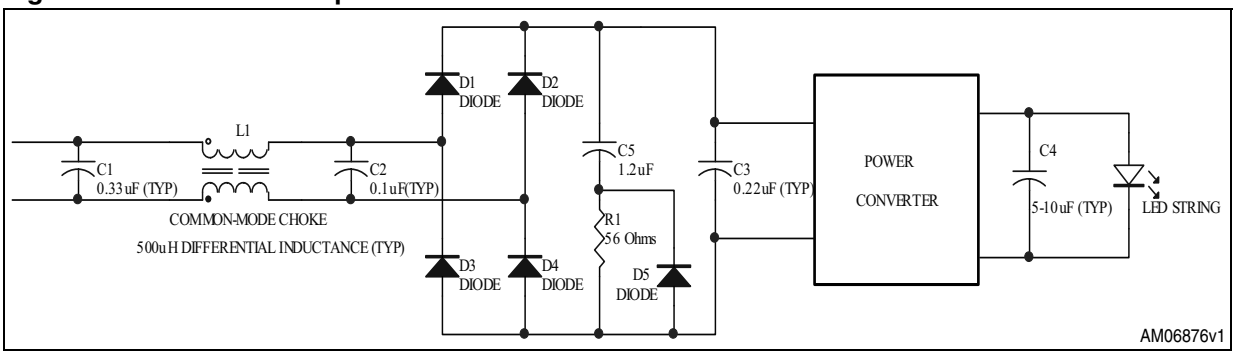
Figure 5 shows a damping network according to our patent application. C5 and R1 provide holding current to the Triac until the filter ringing dies down. If properly sized, ringing is minimized with little loss. The values shown are appropriate for about 30-60 W output.

Figure 5. Adding a damper to the EMI filter



At high power levels (50 W +) load current can easily exceed the current supplied by the filter and damper capacitors between line peaks and zero crossings. The addition of a diode reduces the heat produced by the damping resistor.

Figure 6. Polarized damper



2 Other input filter effects

2.1 Line impedance affects input filter damping

Dimmer Triacs turn off if the current running through them is not maintained above the holding current of about 30 to 50 mA. If the input filter rings, holding current can be interrupted. The Triac must then wait for its next trigger pulse. This can result in severe flicker.

Most of the lab testing had been carried out with a standard VARIAC and step-up transformer, not realizing that the impedance of this source was rather high. The series inductance and winding resistance changed the input filter's characteristics, masking a badly underdamped input filter design.

User demonstrations invariably occur in various settings, which may have heavy wiring with the line possibly loaded with incandescent lamps. These factors reduce the line impedance, exposing the input filter's damping weaknesses.

2.1.1 Control and reduce the line impedance range

The problem can be easily solved. The inductance of the transformer/VARIAC combination was measured (short the line input, measure the output) and a small inductance was added. This process seems to have worked and conducted emissions improved slightly.

2.1.2 Discrete inductor

It was found that 500 µH was enough to stabilize the line impedance. Higher values were chosen to guarantee stability and improve conducted EMI.

2.1.3 Common-mode choke differential L

The discrete inductor can be incorporated into a common-mode choke, but the choke's rated common-mode inductance is NOT what matters. The leakage inductance, or differential mode inductance, is the property to be exploited. This models as an inductance in series with one of the windings, just like in a transformer.

2.1.4 How to measure leakage inductance

Leakage inductance is measured by shorting one of the coils and measuring the inductance of the other winding. Alternately, the windings can be wired in series opposing (connect either input or output pins together and measure the other pair).

For 10 mH through 80 mH bobbin-wound chokes, the typical leakage inductance values are in the 100 µH to 1000 µH range.

2.1.5 Coil separation

Leakage flux is the flux that is not coupled by both windings. It is generally proportional to the spacing between the coils and the square of the turns count. Four-winding common-mode chokes with the same ratings usually have higher leakage inductance in addition to their improved high-frequency filtering (two-section chokes have higher capacitance from input side to output side).

Physically larger chokes have higher leakage inductance, and lower resistance, which contributes to better efficiency.

EMI filter design is a skill that must take the available space, cooling, magnetic coupling, and many other considerations into account. A thorough treatment is, unfortunately, beyond the scope of this paper.

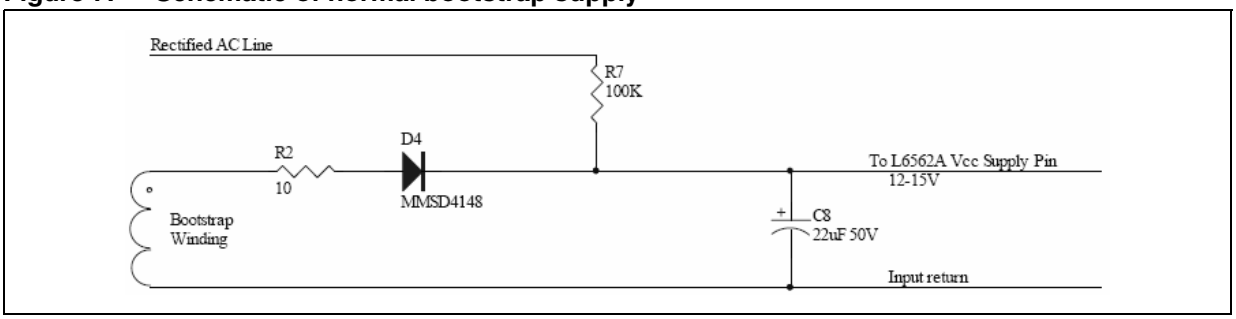
2.2 Powering the control circuits

It has been found that the best way to avoid flicker and flash at turn-off is to have the converter running all the time. This requires control power to be present continuously. If the converter is running it draws holding current, keeping the dimmer Triac in conduction between triggering and zero crossing.

The dimmable LED driver in *Section 4: Hardware design of the STEVAL-ILL016V2 demonstration board*, uses a classical PFC-flyback power converter, controlled by ST's L6562A. This chip operates safely from an unregulated power supply between 12 V and 22 V.

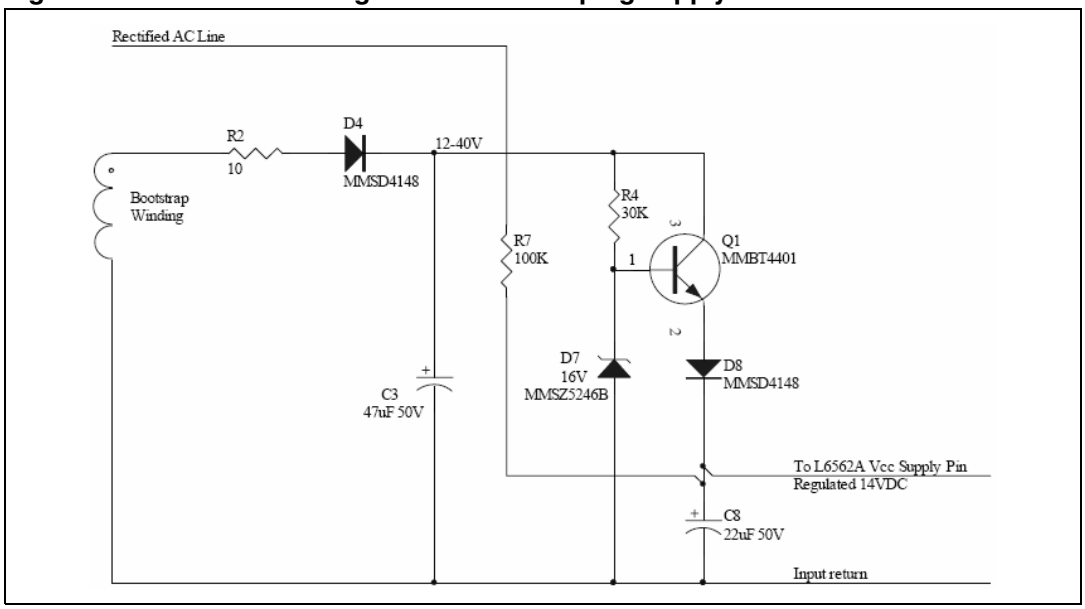
In normal power supplies, with a fixed voltage load and no phase-control, it is easy to meet this range. A primary-side bootstrap winding in phase with the load winding provides the housekeeping power, and the load voltage regulates it by the transformer turns ratio.

Figure 7. Schematic of normal bootstrap supply



Driving LEDs from a Triac-controlled source presents a different problem. When the dimmer is set low, the power source is not present for most of the cycle, and the average LED current is very low. Bootstrap voltage ranges of 3:1 from full-on to full-dim are common. The housekeeping supply must be regulated to cover this very wide range of line voltage and load current.

Figure 8. Schematic of regulated housekeeping supply



The resistor labeled R2 in *Figure 8* above can be used to trim the bulk voltage on C3. Small values (0-10 Ω) allow the leakage spike from FET turn-off to peak-charge C3, while larger values (50-100 Ω) suppress the leakage spike and charge C3 to a voltage regulated by the LEDs and the transformer turns ratio.

3 Filtering the LED current - electrolytic capacitors revisited

3.1 Strobe effects

Earlier designs used only a few microFarads (µF) of filter capacitors across the LEDs. When the dimmer was turned right down, current flowed for less than 1 millisecond out of each half cycle. The result was that rapidly moving objects appeared as multiple stationary images, similar to the appearance of a hand moving rapidly in front of an old TV screen. Reflections from moving shiny objects such as jewelry appeared as dotted lines in the air.

Many users had noticed the effect. The collective opinion was that LED peak-to-peak ripple current should be less than 20 % to 25 % of the average current. The use of electrolytic filter capacitors had to be reconsidered.

3.2 Benefits of electrolytic filters

Once it was understood that very large output capacitors were required, other advantages of their use became apparent.

3.2.1 Reduced crest factor in LEDs

The bonding wires in LEDs are very small - sometimes almost invisible. High RMS current causes the wire to heat the bonding point on the LED die, leading to failure. The RMS current of a power factor controlled converter is higher than necessary for the same light output, by about 1.2 times. Resistive heating is about 45 % higher than for pure DC for the same average current.

3.2.2 Better regulation of housekeeping voltages

With a narrower range of peak current, the LED load voltage range is considerably narrower. Reflected voltage, even with dimming, is much better controlled.

3.3 Electrolytic life calculations

An LED life cycle is advertised as 50,000 to 100,000 hours of operation at 70 % light output. The driver electronics should be designed to match or exceed this.

A capacitor life cycle is rated at maximum operating temperature and maximum ripple current, which typically adds 10 °C to the core temperature. The life cycle doubles for every 10 °C reduction in core temperature. So, for a 105 °C capacitor rated for 10,000 hours at 1 A of ripple current, operated continuously at 85 °C case temperature and 1 A ripple current, a life cycle of 40,000 hours can be expected.

In the real world, continuous 85 °C temperatures are rare. A minimum of double the calculated life cycle can be expected. So, with the proper choice of capacitors, the life cycle can be in the same range as the LED life cycle, and is, therefore, no longer a serious concern.

3.4 Selecting the filter capacitors

The current waveform at the converter output has two fundamental components, one at the switching frequency and one at twice the line frequency.

Ignoring the switching frequency component, the filter capacitor's 120 Hz reactance is sized to limit the ripple current in the LEDs by limiting the applied ripple voltage. This voltage appears across the dynamic resistance of the LEDs.

There are two mechanisms in electrolytic capacitors that cause heating, I2R loss due to ripple current on ESR in the foil at high frequencies, and dissipative losses due to changes in voltage at low frequencies (dissipation factor, similar to hysteresis losses in magnetics). These two effects are additive - both should be considered. While ripple current at the switching frequency is significant, selecting low ESR capacitors and choosing the capacitor value for 120 Hz (see below) generally gives good results.

3.4.1 LED slope resistance (dynamic impedance)

The dynamic impedance of LEDs, like all forward-biased diodes, is inversely proportional to forward current. So, fortunately, as forward current is reduced and the current pulses from the converter become narrower, the same parallel capacitance gives roughly the same ratio of ripple current to average current.

As a rule of thumb, a typical 1 W LED (3.5 V, at 350 mA) has a slope resistance of about 1 Ohm. So, LED dynamic resistance is about 1/10 of total LED voltage divided by total LED current.

3.4.2 Capacitor values

The capacitor value formula below gives good 120 Hz ripple results:

C = 0.1xIavg/Vavg

For a series string of 8 1-W LEDs, the required capacitance is then 0.1*0.35 A/(3.5 V*8), or about 1250 µF.

3.5 Feedback loop characteristics

Abrupt changes of light level appear as flashes to the eye, which has a response time in the range of ¼ second. The control loop is intentionally made very slow (1-5 seconds response time) to smooth the transitions - the eye adjusts to the slow changes. During the transitions, current may be higher than the LED's continuous rating, but no damage can occur - 5 seconds of 20 % overload is not serious.

3.6 Regulating the LED current

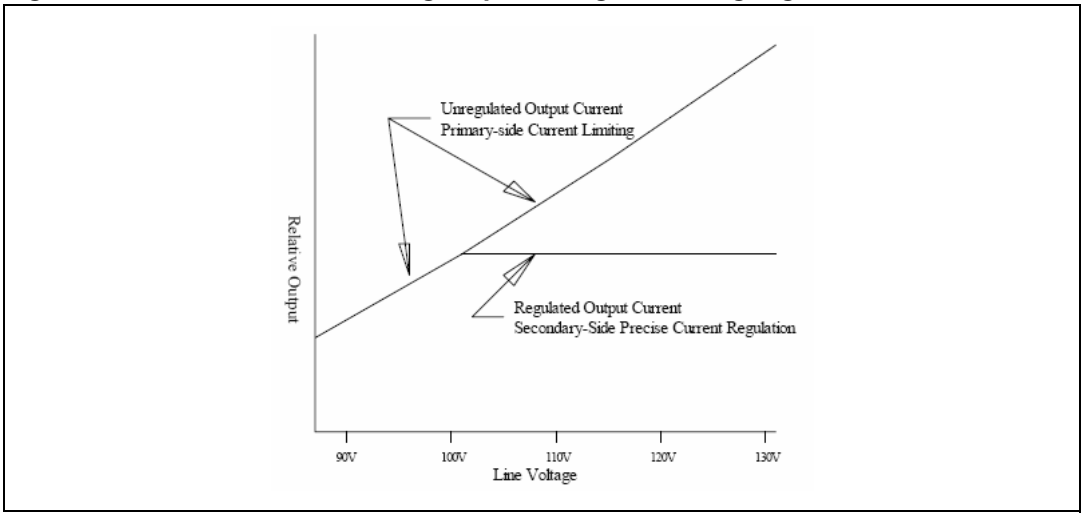
It is desirable for the drive circuit to regulate LED current if a dimmer is not present. In the US, the current should be maintained within +/-5 % between 96 V and 132 V input.

A feedback loop is used to control the current in the undimmed state. See the circuit description in *Section 5* below for details.

When a dimmer is used, the system allows the LED current to fall below the regulation point. The feedback loop is saturated, calling for all the current the flyback converter can deliver.

Primary-side current limiting is used to reduce the LED current - when the dimmer is phased back, average power to the LEDs is reduced. The system is run open-loop when dimmed.

Figure 9. LED current vs average input voltage, showing regulation takeover



3.7 Acoustic noise

The fast rising edges of voltage and current produced by the Triac results in a buzzing noise, worst at about 90 degrees conduction. This can be produced by many parts, though principally magnetics - varnish helps, but they may need to be dipped in epoxy or the assembly potted in silicone.

Also at fault are capacitors, both film caps and ceramics. The film capacitors become electrostatic loudspeakers, the ceramics become piezoelectric speakers. Again, potting or dipping in conformal silicone helps. About 1/8" of silicone on both sides of the PCB is usually enough to silence surface mounted parts.

4 Hardware design of the STEVAL-ILL016V2 demonstration board

Design goals

- Input: 96-132 V_{AC}, 60 Hz, Triac dimmable
- Output: approximately 15 W into LED load, scalable to higher power

Features

- Drives strings of 4 to 14 series-connected white LEDs, jumper selectable
- 15 W, up to 1A output (setup for 350 mA as shipped)
- Undimmed power factor greater than 0.97
- LED current ripple less than 20 % P-P
- Isolated output for safe LED heatsinking

The design uses a single-stage PFC flyback converter, which saves space, costs, and components. The PFC-flyback converter does away with the large input capacitor (usually an electrolytic) and replaces it with a small film capacitor. The input current waveform is then shaped to match the input voltage, and the input current level is adjusted to give the required output. Power factors above the commercial application required 0.9 are easy to meet. Residential required 0.7 power factors are of course met, and the 0.9+ undimmed performance of the device is a strong competitive advantage.

STMicroelectronics devices

- PFC controller: L6562A
- Switching FET: STP5NK60ZFP
- Clamp diode: STTH1R06
- Output diode: STPS10150C
- Current regulator: TSM1052

Figure 10. Image of PC board

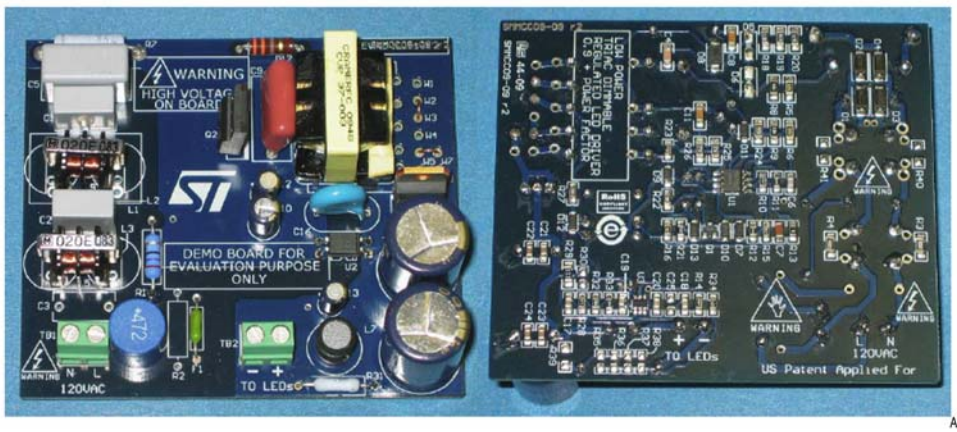
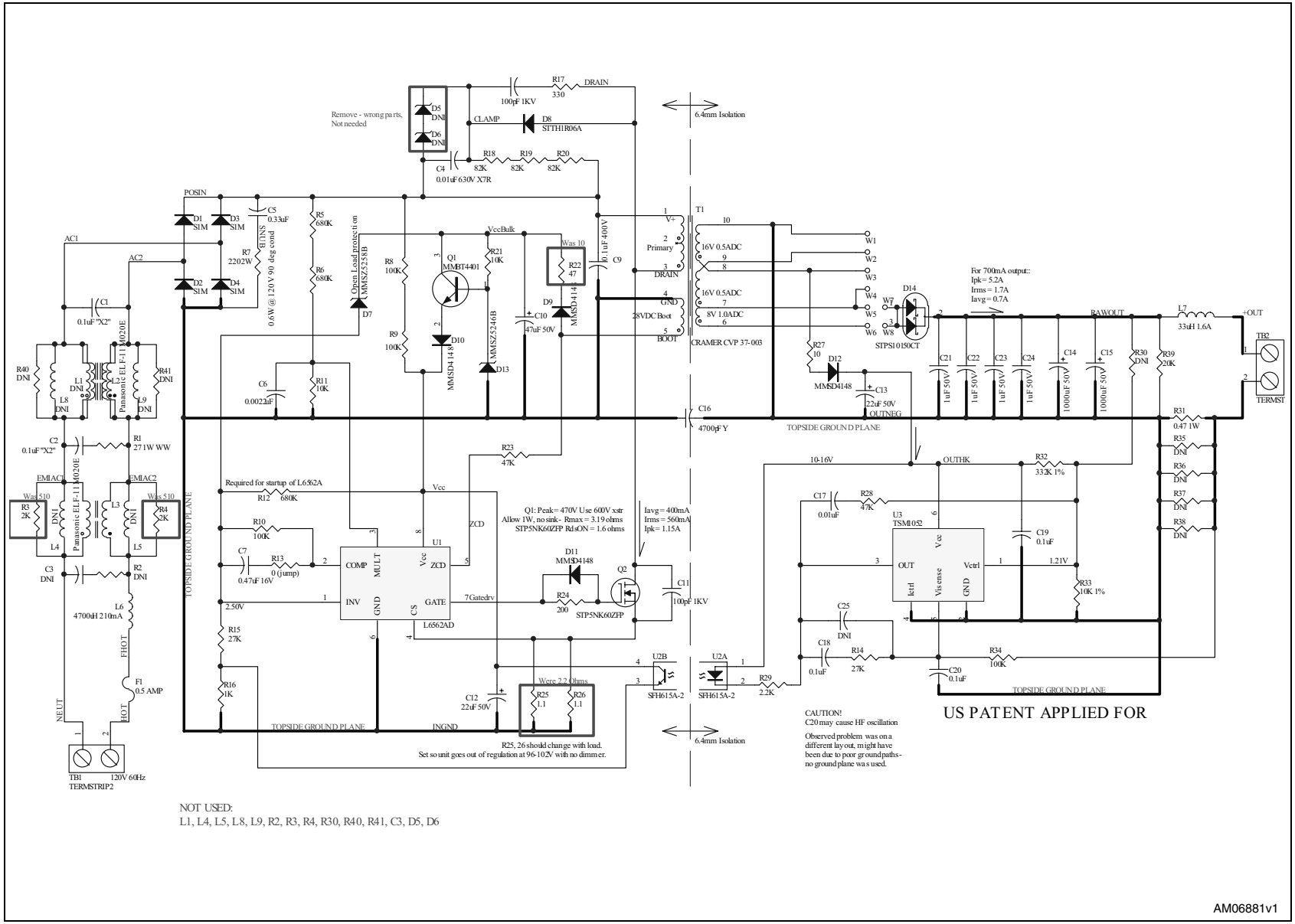


Figure 11. Schematic diagram



5 Circuit description

The unit is basically an AC-DC converter, with the output current regulated rather than the voltage. The topology of the power converter is the transition-mode flyback circuit, with ST's L6562A controller programming the input current to follow the input voltage. ST's TSM1052 feedback controller minimizes current sensing losses on the secondary side.

The required input EMI filtering can present a ringing current to the dimmer's Triac. If the current rings below the Triac's holding current, or reverses, the Triac turns off and the dimmer attempts to start a new half cycle. As the voltage seen by the Triac no longer resembles the expected sine wave at zero crossing, the Triac fires again at an unpredictable time. The result can be severe flicker. R7 and C5 provide damping for the input filter, preventing the ringing from cutting off the holding current.

Operation of the L6562A PFC controller is described in its data sheet, L6562A; *Transition-mode PFC controller,* and various application notes for ST's L6561 and L6562 can be consulted for additional information. AN1059; *Design Equations of High-Power-Factor Flyback Converters Based on the L6561*, is particularly helpful in explaining the PFC-flyback power converter.

Housekeeping power for the L6562A is supplied by the normal trickle start circuit (R8, R9, C12) at startup. After startup, sustaining power from the converter is regulated by Q1. Regulation is necessary for dimmed operation due to the wide range of voltage reflected from the LEDs.

The unit regulates the LED current through two methods.

Operating at dimmed or at low input voltage, the LED current is limited by the primary peak current limit, set by R10:(R15+R16), and the FET source resistors R25-R26. LED current tracks the line voltage in this range - the feedback signal from U2 is zero. R5, R6, R11, and C6 provide the reference waveform (rectified line voltage) for the current-controlled converter.

In undimmed operation, the slow current control loop (U3, TSM1052) takes over to insure the LED current is safely regulated. The feedback signal from opto-isolator U2 adjusts the average regulated current supplied to the LEDs by reducing the COMP input to the L6562A's multiplier. The current control loop is intentionally very slow - rapid action appears to the eye as flashing or flicker when the dimmer is adjusted beyond the regulation point.

U3's voltage loop provides open-load protection. If the load is always present, C17, R30, R32, and R28 can be eliminated.

R27, D12, and C13 provide secondary-side housekeeping power.

C21-C24 filter the output of the converter at high frequencies. At the switching frequency, they shunt the high peak flyback current from the converter away from the LEDs. These may be sufficient if dimmed operation is not required, and they can be eliminated if C14 and C15 are used.

At 120 Hz, electrolytics C14 and C15 reduce the LED ripple current to eliminate strobe effects at low dimmer settings. (Peak-to-peak ripple current of 20-25 % of the DC average is the usual specification).

R31 and R35-R38 set the LED current regulation point. Regulated current is 0.1716 V divided by the parallel resistance. (The unusual sense connection is needed because a high-impedance input is required for the current feedback signal. The reference voltage is

lower than the usual 0.2 volts as a result of moving the reference return from the current sense point to ground) The demonstration board is supplied with a 0.47 Ω resistor at R31, giving current regulation at about 370 mA.

If there is a danger of short-circuit at the LED output, at least one of the resistors in the current sense locations should be wirewound. The electrolytic filter caps store enough energy to burn out surface mounted thick or thin film resistors.

The power transformer has two secondary windings and a tap to accommodate series strings of 4 to 14 LEDs. *Table 1* shows proper connections, and recommends filter capacitors for the various tap configurations. Total power output should be kept below about 15 W to avoid overheating the input filter and other components.

Table 1. Jumper and capacitor selection table

# LEDs in series strings	Current, Amps, max	Jumpers	C14, C15 filter capacitors	Filter cap size
4-5	1 A	W1-W2, W3-W4, W5-W7	2 x 3900 uF 25 V Panasonic EEU-FC1E392L	16 mm dia x 36 mm high
6-7	1 A	W1-W2, W3-W4, W6-W8	2 x 2700 uF 35 V Panasonic EEU-FC1V272L	16 mm dia x 32 mm high
8-10	0.5 A	W2-W3, W5-W7	2 x 1000 uF 50 V Panasonic EEU-FC1H102	16 mm dia x 25 mm high
10-13	0.5 A	W2-W3, W6-W8	2 x 820 uF 50 V Chemi-Con ELXY500ELL821ML25S	16 mm dia x 25 mm high

Table 2. Current set resistor selection

Total LED current	R31, or parallel combination of R31 and R35-R38
350 mA	0.5 Ω
700 mA	0.25 Ω
Other	R = 0.1716/Iout

6 Performance

6.1 Undimmed performance

6.1.1 Setup for minimum dimmable output

9 W out, 8 series LEDs, jumpers at W2-W3, W5-W7. 9 Watts output is about the minimum that most triac-based dimmers will tolerate without flicker. Holding current is an issue below that loading.

Figure 12. 96 V input voltage 9 W, 8 series LEDs

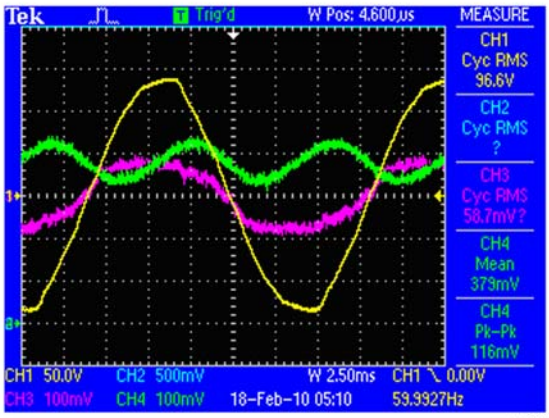
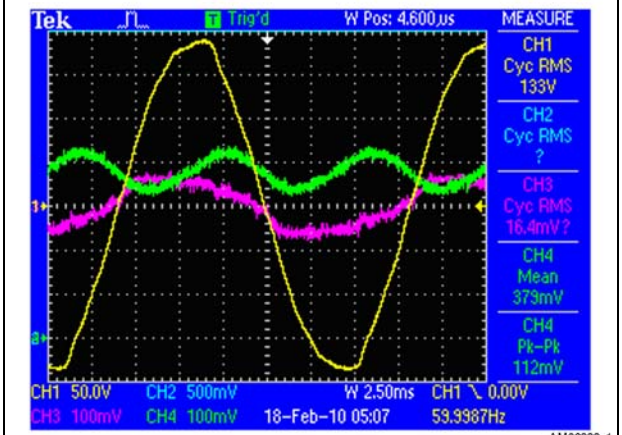


Figure 13. 132 V input voltage 9 W, 8 series LEDs



Trace colors:

- Yellow = line voltage, 100 V/div
- Magenta = line current, 200 mA/div
- Green = LED current, 100 mA/div
- Load: 2 strings of 8 (1 W) LEDs

Table 3. Performance at 9 W into 8 series LEDs

Parameter	Very low line	Low line	Nominal line	High line
Line voltage	96	108	120	132
Line current, mA	116.8	104.5	94.9	87.4
Input power, Watts	10.96	10.89	10.87	10.89
Power factor	0.9766	0.9665	0.9528	0.9735
Output voltage	23.96	23.96	23.97	23.98
Output current, mA	371	371	371	371
Current ripple, mA P-P	120	128	120	116
Output power	8.89	8.89	8.89	8.89
Efficiency, %	81.1	81.6	81.8	81.6

6.1.2 Setup for greatest voltage stresses

12 W out, 11 series LEDs, jumpers at W2-W3, W5-W7.

Figure 14. 96 V input voltage

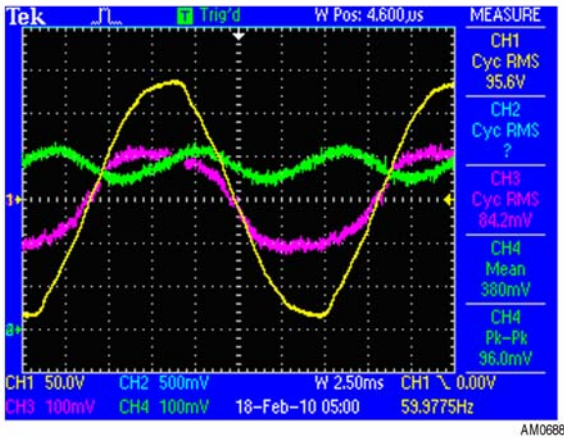


Figure 15. 132 V input voltage

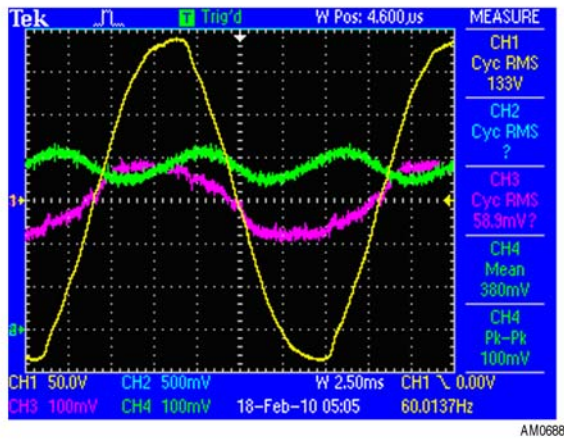


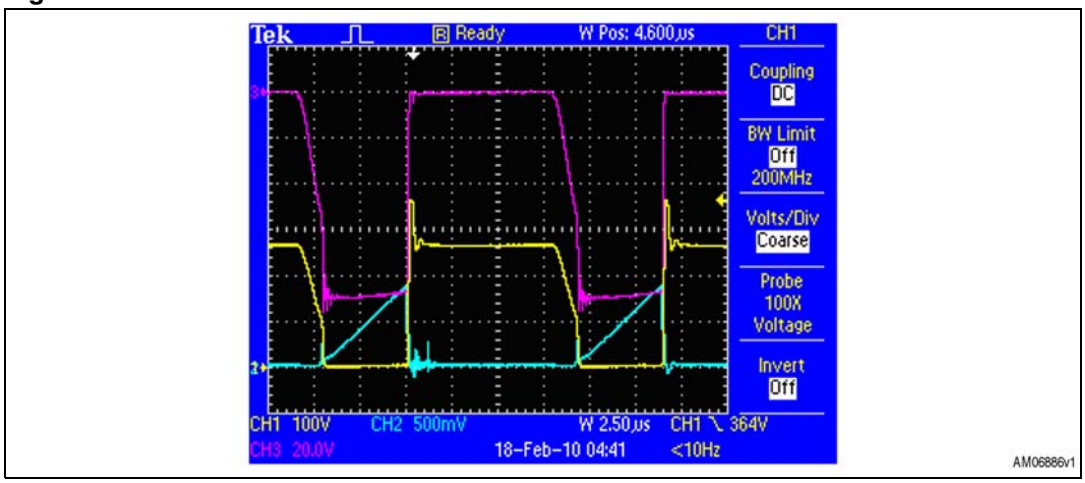
Table 4. 12 W into 11 series LEDs

Parameter	Very low line	Low line	Nominal line	High line
Line voltage	96	108	120	132
Line current, mA	164.3	143.6	128.9	116.9
Input power, Watts	15.45	15.17	15.05	15.00
Power factor	0.9853	0.9816	0.9745	0.9638
Output voltage	33.39	33.25	33.23	33.20
Output current, mA	371	371	371	371
Current ripple, mA P-P	92	100	96	96
Output power	12.39	12.34	12.33	12.32
Efficiency, %	80.1	81.3	81.9	82.1

Component stresses

The tap configuration with jumpers at W2-W3 and W5-W7 with 11 series LEDs maximizes the volts per turn on the transformer. Stress on the bootstrap diode, D9, is too great. A 200 V diode should be used at that location if the maximum number of LEDs in a string is used for each jumper configuration.

Figure 16. Stress on FET and diode



- Yellow = Q2 drain voltage, 100 V/div
- Blue = Q2 current (actually the voltage across R25 and 26)
- Magenta = voltage on D9 (bootstrap), rated for 100 V, 20 V/div

Figure 16 above was taken with 132 V_{AC} input, near the peak of the input sine wave. The transition-mode operation is clearly visible - the drain voltage (yellow trace) begins to fall as the output diode stops conducting, at 6.2 divisions. Gate drive (not shown) comes on at 6.7 divisions, and the drain voltage falls to zero. Drain current (blue trace) then begins to rise, with only a minimal current spike as stray capacitance is discharged. The gate is turned off at 8.6 divisions, and the drain voltage rises abruptly due to flux stored in the transformer air gap. The drain voltage overshoot is due to leakage inductance in the transformer - the drain current is caught by D8, and the leakage energy is dumped into C4.

6.1.3 Setup for maximum power

16 W out, 10 series LEDs, jumpers at W2-W3, W6-W8, 0.5A:

Trace colors:

- Yellow = line voltage, 100 V/div
- Magenta = line current, 200 mA/div
- Green = LED current, 100 mA/div

Figure 17. 96 V line 16 W, 10 series LEDs

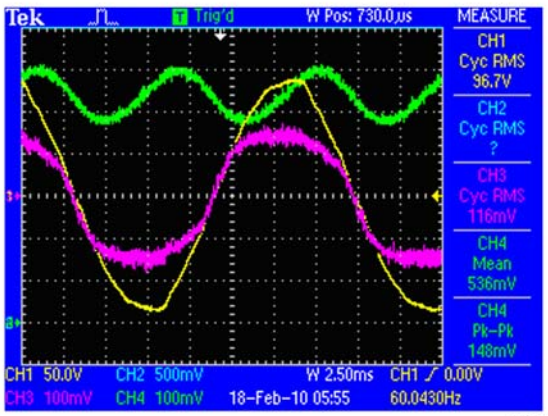


Figure 18. 132 V line 16 W, 10 series LEDs

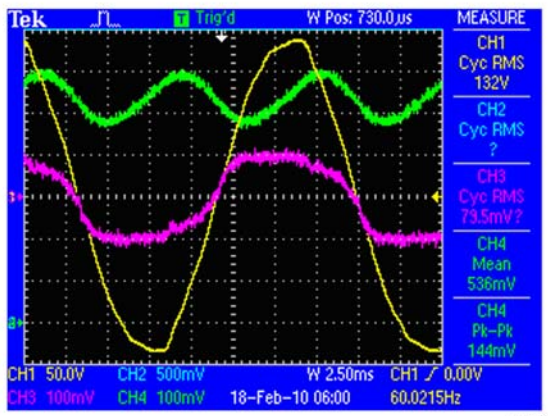


Table 5. Performance at 16 W into 10 series LEDs

Parameter	Very low line	Low line	Nominal line	High line
Line voltage	96	108	120	132
Line current, mA	227	195.2	171.0	154.4
Input power, Watts	21.42	20.67	20.08	19.77
Power factor	0.9855	0.9813	0.9756	0.9686
Output voltage	30.84	30.79	30.77	30.75
Output current, mA	0.528	0.528	0.528	0.528
Current ripple, mA P-P	152	144	148	144
Output power	16.28	16.26	16.25	16.24
Efficiency, %	76.0	78.6	80.9	82.1

This configuration uses the transformer at maximum current in the full series connection. A 1 Ω resistor has been placed at R36 to increase the regulated current to slightly over the 1/2 A limit. The efficiency hit at low input voltage is mostly due to I2R loss in the input filter.

6.1.4 Setup for maximum output current

16 W out, 5 series LEDs, jumpers at W1-W2, W3-W4, W6-W8.

Figure 19. 96 V input 16 W, 5 series LEDs

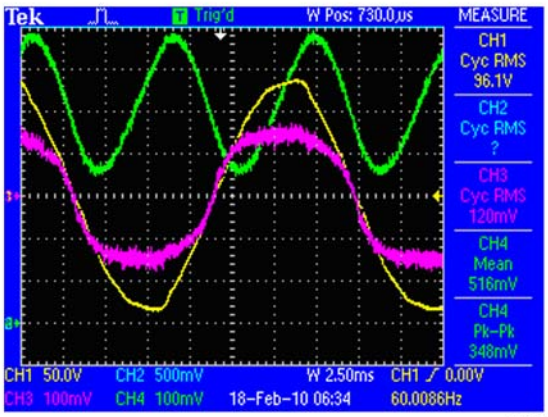


Figure 20. 132 V input 16 W, 5 series LEDs

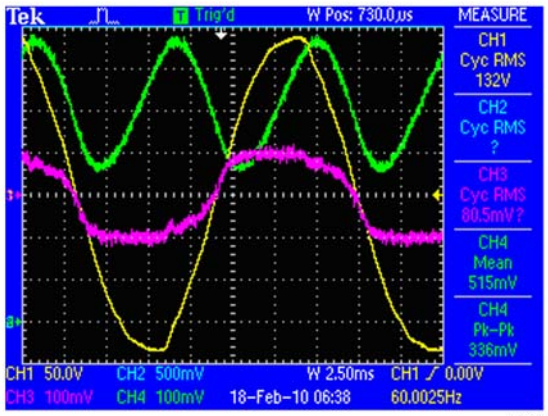


Table 6. Performance at 16 W into 5 series LEDs

Parameter	Very low line	Low line	Nominal line	High line
Line voltage	96	108	120	132
Line current, mA	232	199.2	175.6	157.2
Input power, Watts	21.85	21.12	20.60	20.25
Power factor	0.9838	0.9803	0.9748	0.9685
Output voltage	15.69	15.65	15.62	15.61
Output current, mA	1019	1018	1017	1017
Current ripple, mA P-P	700	680	672	656
Output power	15.99	15.93	15.88	15.88
Efficiency, %	73.1	75.4	77.1	78.4

The configuration above uses the full secondary in high-current low-voltage mode. The effects of the secondary diode drop (D14) are evident in the efficiency. A lower voltage Schottky diode or a synchronous rectifier would help.

Table 7. Undimmed temperatures, configured as above (worst case), 120 V input

Component	Measured	Component	Measured
L6	38.7	Q2	51.9
L3	57.5	D14	41.0
L2	75.8	L7	39.9
D2	53.5	T1	59.5
R7	51.2	Ambient	26.7

6.2 Dimmed performance

Conditions: 120 V input, into 2 parallel strings of 8 LEDs

Figure 21. Dimmer at maximum output

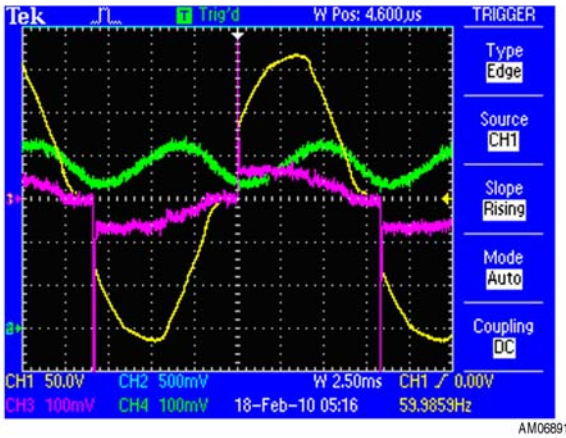
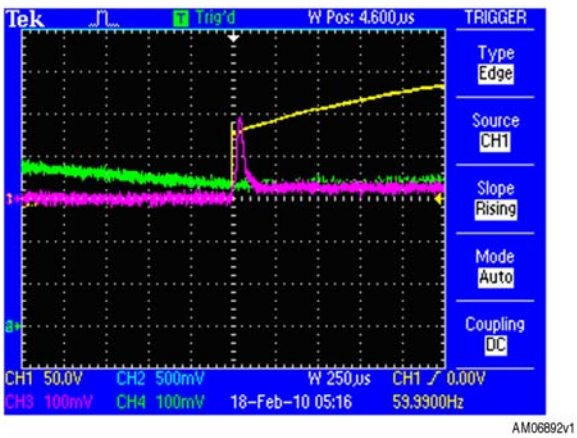


Figure 22. Detail of line current (magenta = 0.5 A/div)



- Yellow = dimmed line voltage, 50 V/div
- Magenta = dimmed line current, 0.2 A/div unless noted
- Green = LED current, 0.2 A/div

The current spike in the magenta trace is about 1 A peak. Note the very small amount of ringing following the leading edge of the current waveform. The current must not be allowed to reverse, or the dimmer Triac turns off, leading to erratic operation and severe flicker.

Figure 23. Dimmer at 90 degrees

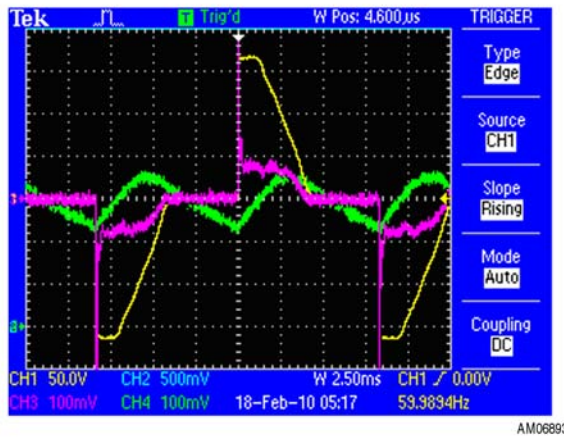
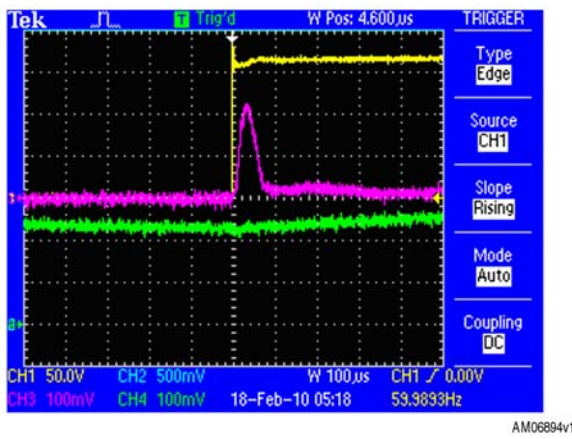


Figure 24. Detail of line current (magenta = 0.5 A/div)



This is the worst condition for ringing after the current transient. Damping is very good. Dimmer just above extinction, LED current = 23 mA.

Figure 25. Dimmer at 90 degrees

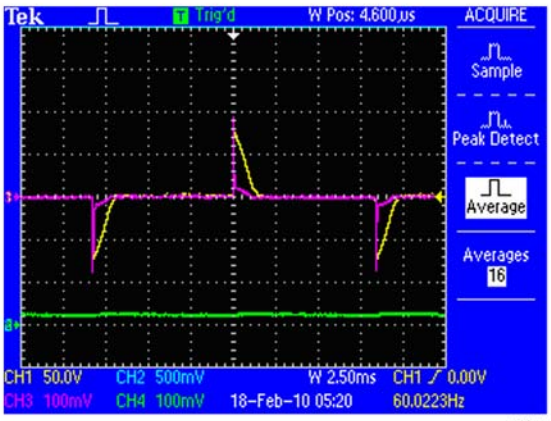


Figure 26. Detail of line current (magenta = 0.5 A/div)

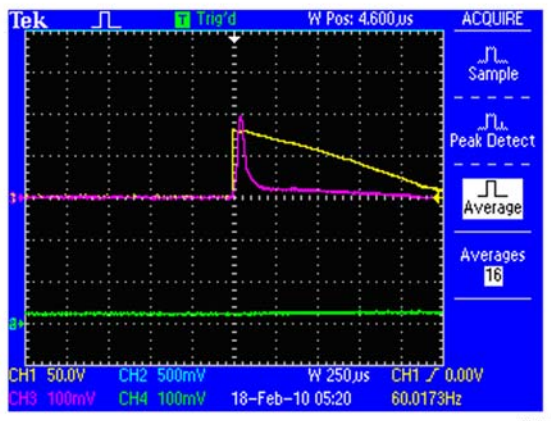


Table 8. Temperatures, unit dimmed to maximum input power, 120 V in(~22.4 W, worst case)

Component	Measured	Component	Measured
L6	49.1	Q2	58.1
L3	89.6	D14	66.9
L2	104.3	L7	40.6
D2	65.3	T1	64.7
R7	80.3	Ambient	24.4

Note that R7, the damper resistor, is stressed only when the line is Triac dimmed. It dissipates very little power when the input is a sine wave. However, it should be moved away from the capacitors.

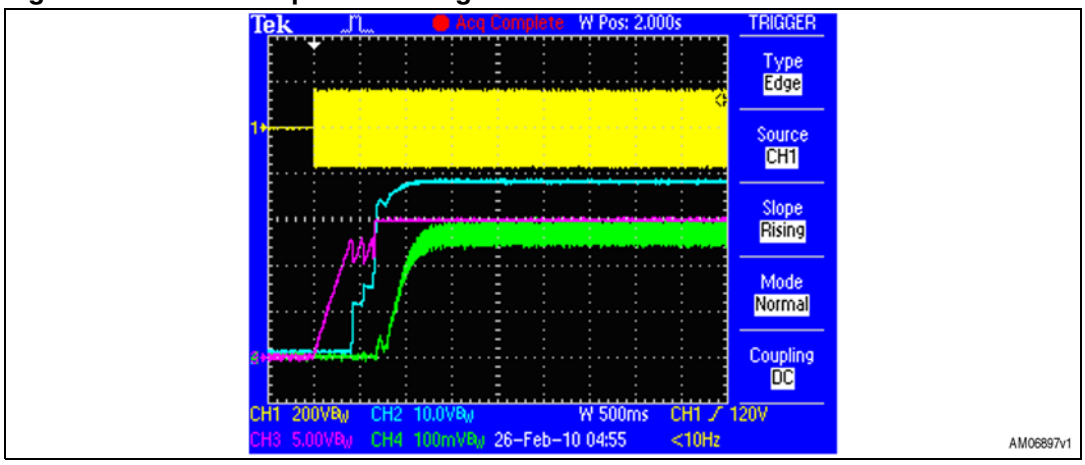
L2 and L3 could use some work. Temperatures are too high, and the conducted EMI plots (in *Figure 28*) show little margin.

6.3 Startup time

Startup scope image - cold start, everything discharged, 12 series LEDs, 0.5 A

- Yellow = AC line, 120 V, 200 V/div
- Magenta = Vcc for L6562A, 5 V/div
- Blue = LED voltage, 10 V/div
- Green = LED current, 200 mA/div

Figure 27. Time from power in to light out



There are some requirements for 1 second startup, some for ½ second, and there is a desire on the part of users to have instantaneous startup - light as soon as the AC is applied.

This unit was optimized for 1 second startup. The LEDs begin to light at 0.7 seconds. Full regulated output is achieved within 1.5 seconds. If faster starts are required, R8 and R9 can be reduced to 22 kΩ each, at the cost of about ¼ W of additional housekeeping power.

6.3.1 Dimmed start issue

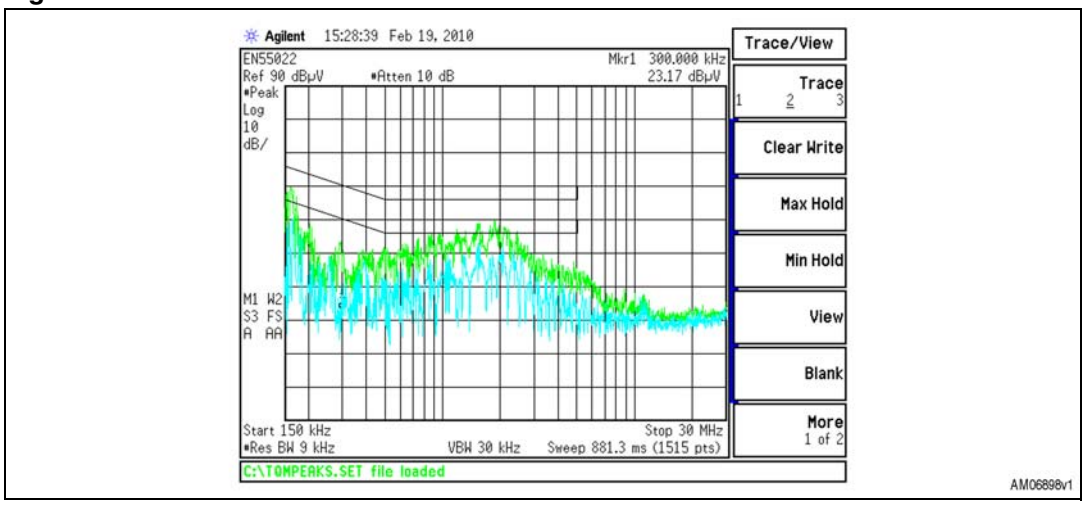
Users have asked for turn-on when dimmed to correspond to the dimmer setting, giving the same light level on turn-on as the dimmer setting gave the last time it was in the same position.

Note that the dimmer must be turned up beyond the 90 degree point for restart after dimming to extinction or turn-off. During the falling edge of each half cycle the reactive current from the input filter capacitors opposes the startup current drawn by the converter. The capacitors supply all the power required by the converter startup. As a result, at low conduction angles, before the converter starts, the dimmer Triac does not see enough holding current to remain on after it is triggered.

6.4 Conducted EMI

Traces shown below are the maximum of 3 successive sweeps (max hold), peak values.

Figure 28. Conducted EMI



The plots show peak noise just above the average limit at 160 kHz and 2 MHz. There is a good chance that the unit passes conducted EMI tests when repackaged.

7 BOM list

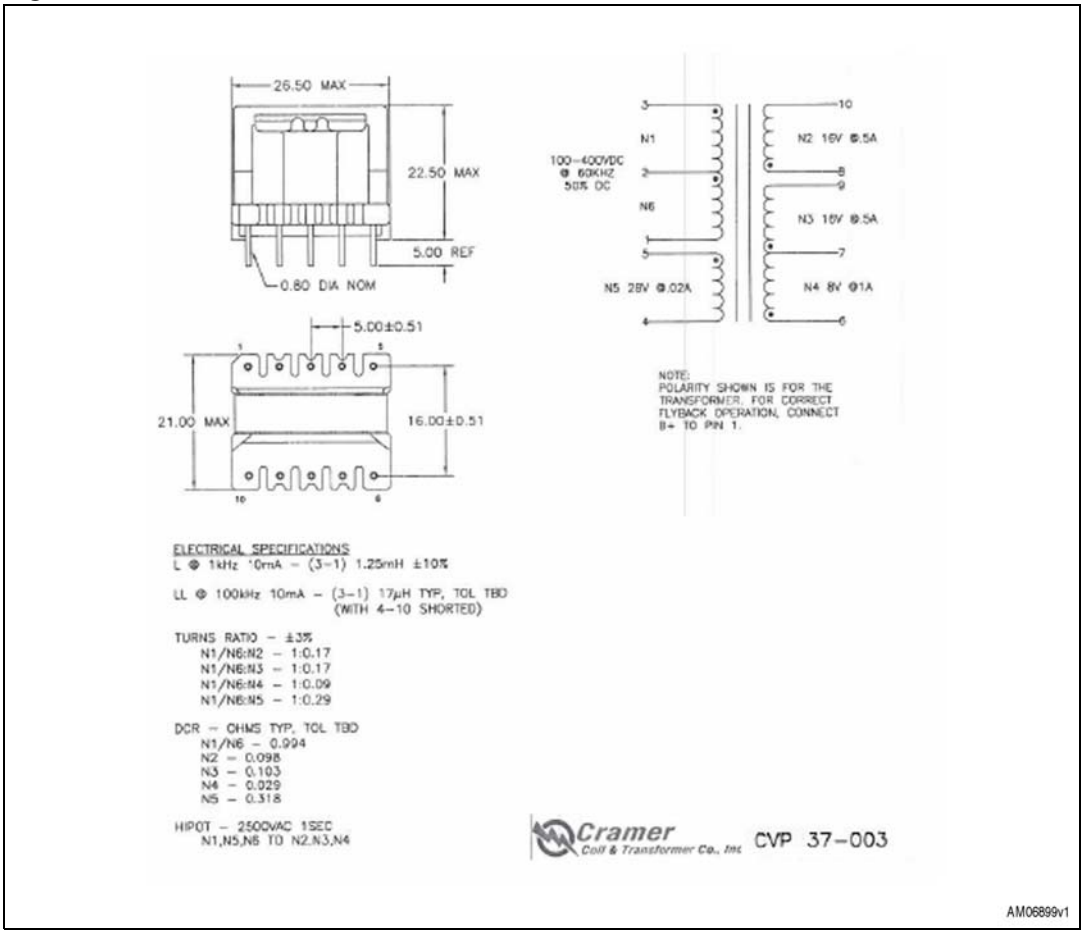
Table 9. BOM list

Designator	Part type	Mfr #
C1,2	0.1 µF “X2”	Vishay 2222 338 20104
C10	47 µF 50 V	Panasonic EEU-FC1H470
C12,13	22 µF 50 V	Panasonic EEU-FC1H220
C14,15	1000 µF 50 V	Panasonic EEU-FC1H102
C16	4700 pF Y	Panasonic ECK-ANA472ME
C17	0.01 µF	X7R 20 % 0805
C18-20	0.1 µF	X7R 20 % 0805
C21-24	1 µF 50 V	Murata GRM21BR71H105KA12L
C3	DNI	Vishay 2222 338 20104
C4	0.01 µF 630 V X7R	Panasonic ECJ-3FB2J103K
C5	0.33 µF	Panasonic ECQ-E4334KF
C6	0.0022 µF	X7R 20 % 0805
C7	0.47 µF 16 V	0805 10 % X7R
C8,11	100 pF 1 kV	AVX 1206AC101KAT1
C9	0.1 µF 400 V	Panasonic ECW-F4104JB
D13	MMSZ5246B	Diodes Inc. MMSZ5246B-7
D14	STPS10150CT	ST STPS10150CT
D1-4	S1M	Diodes Inc. S1M-13-F
D5,6	DNI	ST SMAJ188A
D7	MMSZ5258B	ON Semi MMSZ5258BT1G
D8	STTH1R06A	ST STTH1R06A
D9-12	MMSD4148	Fairchild MMSD4148
F1	0.5 A	Littelfuse 0251.500MXL
L1	DNI	*
L2,3	Panasonic ELF-11M020E	Panasonic ELF-11M020E
L4,5,8,9	DNI	TDK TSL1112RA-472JR21-PF
L6	4700 µH 210 mA	TDK TSL1112RA-472JR21-PF
L7	33 µH 1.6 A	J.W.Miller RL622-330K-RC
Q1	MMBT4401	Diodes Inc. MMBT4401-7 or Fairchild MMBT4401
Q2	STP5NK60ZFP	ST STP5NK60ZFP
R1	27 1 W WW	Huntington ALSR-1-27
R10,34	100 kΩ	5 % 0805

Table 9. BOM list (continued)

Designator	Part type	Mfr #
R11,21	10 kΩ	5 % 0805
R12	680 kΩ	5 % 0805
R13	0 (jump)	0805 Zero-Ohm Jumper
R14,15	27 kΩ	5 % 0805
R16	1 kΩ	5 % 0805
R17	330 Ω	RES 0.5W 5 %
R18-20	82 kΩ	5 % 1206
R2	DNI	Huntington ALSR1J-27
R22	47 Ω	5 % 0805
R23,28	47 kΩ	5 % 0805
R24	200 Ω	5 % 1206
R25,26	1.1 Ω	5 % 1206
R27	10 Ω	5 % 0805
R29	2.2 kΩ	5 % 1206
R3,4	2 kΩ	5 % 1206
R30,35-38; C25	DNI	5 % 0805
R31	0.47 1 W	Panasonic ERX-1SJR47
R32	332 kΩ 1 %	1 % 0805
R33	10 kΩ 1 %	1 % 0805
R39	20 kΩ	5 % 1206
R40,41	DNI	5 % 1206
R5,6	680 kΩ	5 % 1206
R7	220 2 W	Panasonic ERG-2SJ221
R8,9	100 kΩ	5 % 1206
T1	CRAMER CVP 37-003	CRAMER CVP 37-003
TB1,2	TERMSTRIP2	Phoenix 1729018
U1	L6562AD	ST L6562AD
U2	SFH615A-2	Vishay SFH615A-2
U3	TSM1052	ST TSM1052

Figure 29. Transformer detail



8 PC layout

Figure 30. Top

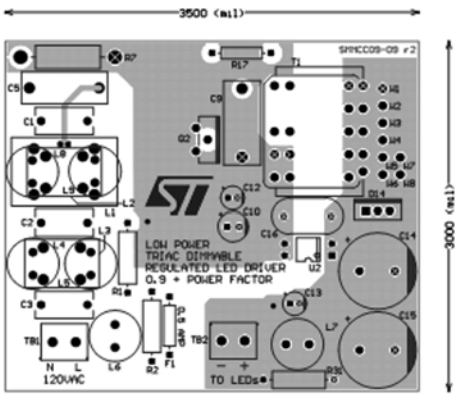
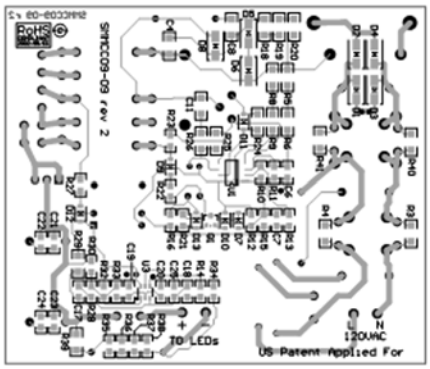


Figure 31. Bottom



Further work

The design has been extended to a 30 W output, on the same printed circuit layout, with very good success. 30 W transformers have been designed to fit the dual footprint for T1.

Similar designs have been produced with a 60 W output.

The input filter has always given problems. It is important to minimize the capacitive current to maintain power factor and dimmability, which means that higher value inductors are required, which increases their DC resistance, which impacts efficiency. It is expected that the user designs their own input filter in most cases. Sufficient space and component pads are available for experimentation.

9 References

- L6562A; *New industry reference transition-mode PFC controller*
- L6562; *Transition-mode PFC controller*
- L6561; *Transition-mode PFC controller*
- AN1059; *Design Equations of High-Power-Factor Flyback Converters Based on the L6561*
- AN1060; *Flyback converters with the L6561 PFC controller*
- TSM1052; *Constant voltage and constant current controller for battery chargers and adapters*

US department of energy

- Multi-Year program plan FY'09-FY'15, solid-state lighting research and development ENERGY STAR® requirements for SSL luminaires, version 1.1

ANSI

- Class 2 definition\
- ANSI C78.377-2008, specifications for the chromaticity of solid-state lighting products
- C82.77-2002 harmonic emission limits - related power quality requirements for lighting
- Specifies the maximum allowable harmonic emission of SSL power supplies.

IES illumination engineering society

- IES LM-79-2008; *Approved method for the electrical and photometric testing of solid-state lighting devices*
- IES LM-80-2008; *Approved method for measuring lumen depreciation of LED Light Sources*
- IES RP-16; *Addendum a, nomenclature and definitions for illuminating engineering*

Underwriters laboratories

- UL 1310 class 2 power units
- Specifies the minimum safety requirements for class 2 power supplies (as defined in NFPA 70-2005).
- UL 1012 power units other than class 2
- Specifies the minimum safety requirements for power supplies other than class 2 (as defined in NFPA 70-2005).
- UL 2108 low voltage lighting systems
- Species the minimum safety requirements for low-voltage lighting systems.
- UL 1574 track lighting systems
- Specifies the minimum safety requirements for track lighting systems.
- UL 1598 luminaires
- Specifies the minimum safety requirements for luminaires. The requirements in this document may be referenced in other documents such as UL 8750 or separately used as part of the requirements for SSL products.

National fire protection association

- 70-2005 National Electrical Safety Code®
- Most SSL products must be installed in accordance with the National Electrical Safety Code®.

Federal communications commission

- 47 CFR Part 15 radio frequency devices
- Specifies FCC requirements for maximum allowable unintended radio-frequency emissions from electronic components, including SSL power supplies and electronic drivers.

Standards in development

- ANSI C82.04, driver performance standard
- ANSI C82.SSL1 power supply
- Specifies operational characteristics and electrical safety of SSL power supplies and drivers.
- IES TM-21, method for estimation of LED life
- IES LM-XX1, methods for the measurements of high power LEDs
- UL 8750 outline of investigation for light-emitting-diode (LED) light sources for use in lighting products
- Specifies the minimum safety requirements for SSL components, including LEDs and LED arrays, power supplies, and control circuitry.

10 Revision history

Table 10. Document revision history

Date	Revision	Changes
20-Mar-2008	1	Initial release
24-Apr-2009	2	Modified: *Figure 27* and *Table 3*
28-Sep-2010	3	Rewritten to reflect new demonstration board, with new information

Please Read Carefully:

Information in this document is provided solely in connection with ST products. STMicroelectronics NV and its subsidiaries (“ST”) reserve the right to make changes, corrections, modifications or improvements, to this document, and the products and services described herein at any time, without notice.

All ST products are sold pursuant to ST’s terms and conditions of sale.

Purchasers are solely responsible for the choice, selection and use of the ST products and services described herein, and ST assumes no liability whatsoever relating to the choice, selection or use of the ST products and services described herein.

No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted under this document. If any part of this document refers to any third party products or services it shall not be deemed a license grant by ST for the use of such third party products or services, or any intellectual property contained therein or considered as a warranty covering the use in any manner whatsoever of such third party products or services or any intellectual property contained therein.

UNLESS OTHERWISE SET FORTH IN ST’S TERMS AND CONDITIONS OF SALE ST DISCLAIMS ANY EXPRESS OR IMPLIED WARRANTY WITH RESPECT TO THE USE AND/OR SALE OF ST PRODUCTS INCLUDING WITHOUT LIMITATION IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE (AND THEIR EQUIVALENTS UNDER THE LAWS OF ANY JURISDICTION), OR INFRINGEMENT OF ANY PATENT, COPYRIGHT OR OTHER INTELLECTUAL PROPERTY RIGHT.

UNLESS EXPRESSLY APPROVED IN WRITING BY AN AUTHORIZED ST REPRESENTATIVE, ST PRODUCTS ARE NOT RECOMMENDED, AUTHORIZED OR WARRANTED FOR USE IN MILITARY, AIR CRAFT, SPACE, LIFE SAVING, OR LIFE SUSTAINING APPLICATIONS, NOR IN PRODUCTS OR SYSTEMS WHERE FAILURE OR MALFUNCTION MAY RESULT IN PERSONAL INJURY, DEATH, OR SEVERE PROPERTY OR ENVIRONMENTAL DAMAGE. ST PRODUCTS WHICH ARE NOT SPECIFIED AS "AUTOMOTIVE GRADE" MAY ONLY BE USED IN AUTOMOTIVE APPLICATIONS AT USER’S OWN RISK.

Resale of ST products with provisions different from the statements and/or technical features set forth in this document shall immediately void any warranty granted by ST for the ST product or service described herein and shall not create or extend in any manner whatsoever, any liability of ST.

ST and the ST logo are trademarks or registered trademarks of ST in various countries.

Information in this document supersedes and replaces all information previously supplied.

The ST logo is a registered trademark of STMicroelectronics. All other names are the property of their respective owners.

© 2010 STMicroelectronics - All rights reserved

STMicroelectronics group of companies

Australia - Belgium - Brazil - Canada - China - Czech Republic - Finland - France - Germany - Hong Kong - India - Israel - Italy - Japan - Malaysia - Malta - Morocco - Philippines - Singapore - Spain - Sweden - Switzerland - United Kingdom - United States of America

www.st.com