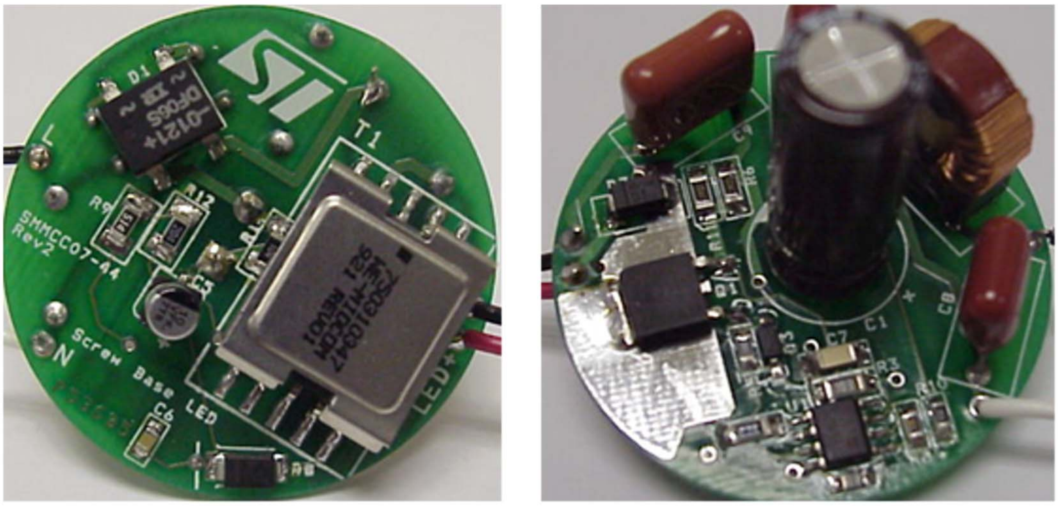
AN3111
Application note

18 W single-stage offline LED driver

Introduction

With the rapid development of high brightness LEDs, SSL (solid state lighting) has begun to move from being a niche market to penetrating residential markets. There is a large potential market for the residential application of SSL, and CFL (compact fluorescent lamp) retro-fit is part of it. Standardization of SSL products is helping to lead the growth of the market. In September 2007, the US department of energy (DOE) issued ENERGY STAR® criteria for SSL products. To meet the ENERGY STAR specifications for SSL products, the power factor of power supply must be higher than 0.7 for residential applications. For CFL retro-fit applications, cost, size, and reliability are very important. To achieve a high power factor, either passive PFC (power factor correction) or active PFC can be used. Typically, passive PFC requires large passive components, which makes it difficult to maintain a small size. Traditional active PFC circuits require a two-stage topology, which entails a boost stage for PFC, and then buck or flyback for current regulation of the LEDs. The cost of the two stages is high. In this application note, a non-isolated, soft-switched, single-stage high power factor offline LED driver is introduced. The buck-boost converter is chosen for this application due to its simplicity and low cost. The converter operates with constant peak current for constant power control, and in transition mode (boundary mode between CCM and DCM) to achieve soft switching, using the L6562A controller. High power factor is achieved by reshaping the peak current near the zero crossing of the input AC line.

Figure 1. 18 W single-stage offline LED driver board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For this particular design, the LED string consists of 18, 1 W white LEDs in series. Isolation is not required. The goal of the design is high power factor, high efficiency, simplicity, and low cost.

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1 Circuit design

The L6562A is a current mode PFC controller operating in transition mode (boundary mode between CCM and DCM). Its linear multiplier enables the converter to shape the AC input current waveform following the input voltage. The block diagram of the L6562A is shown in *Figure 2* below. For more detailed information regarding the L6562A, please refer to the device datasheet and application notes.

Figure 2. Block diagram for the L6562A

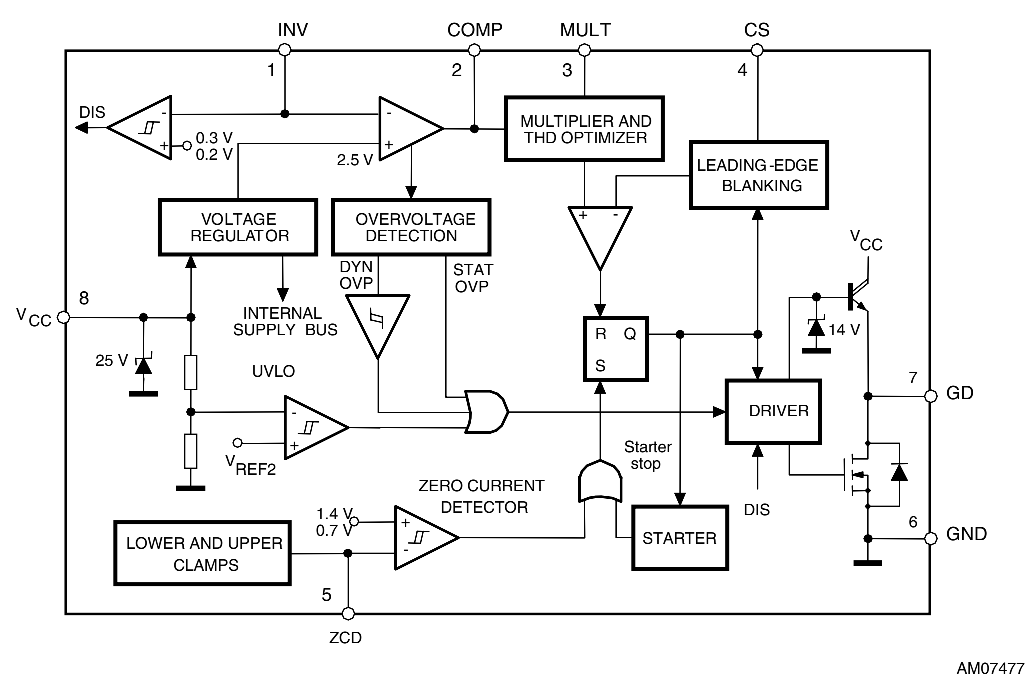
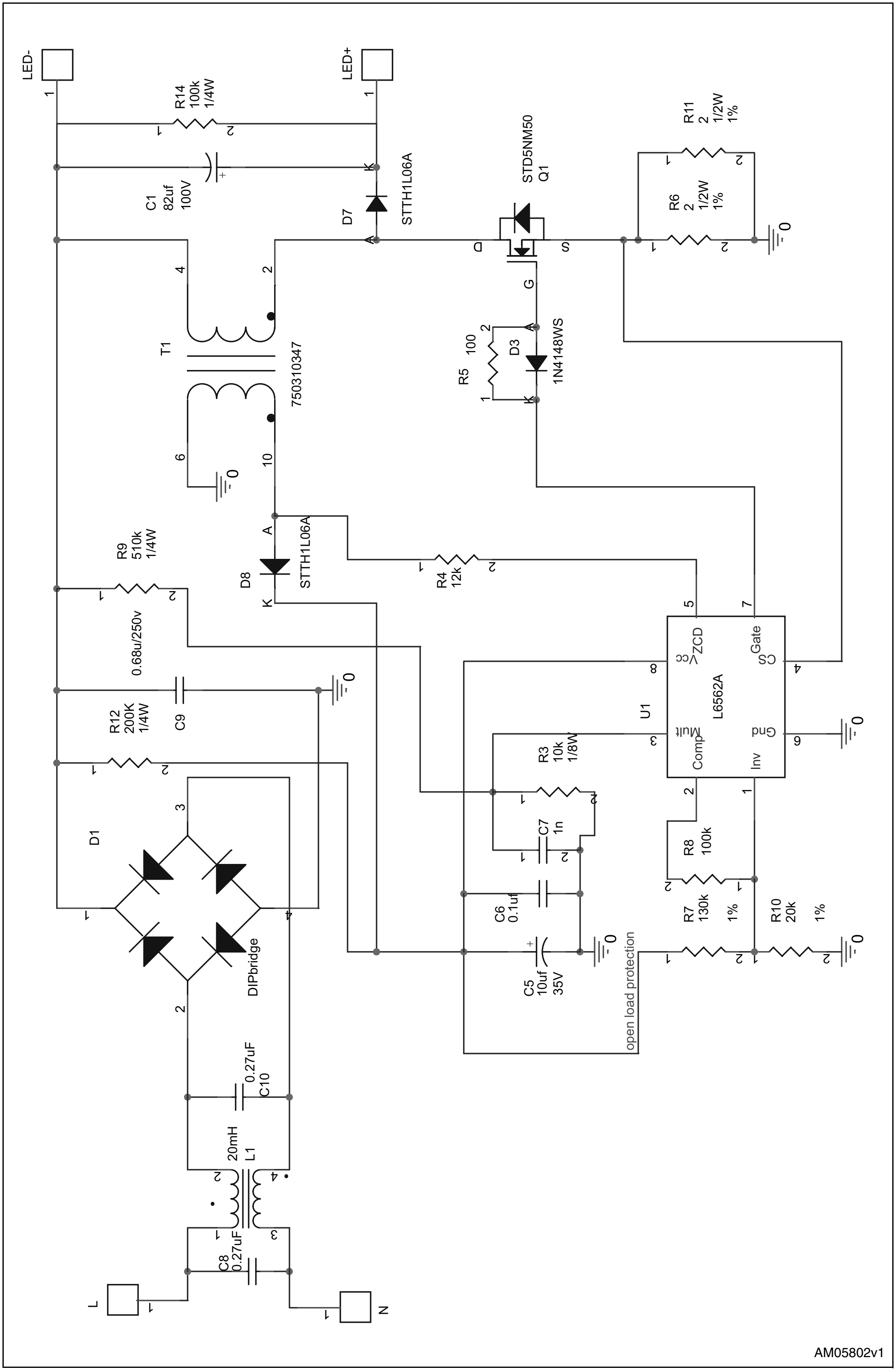


Figure 3 shows the schematic of the proposed single-stage LED driver. If the inductor current is constant, the power of the converter is constant. As the LED string is a constant voltage load, we can obtain a constant current in the LED string. This makes it possible to leave out the LED current sensing, therefore simplifying the circuit design. If the inductor current is constant, then the power factor of the circuit is very poor. The input current waveform is greatly distorted during line voltage zero crossing. If there is a way to reduce the current amplitude near the line voltage zero crossing, the power factor can be improved. The L6562A PFC controller is used to achieve this objective. The idea is to reduce the current amplitude near the line voltage zero crossing, which results in an improved power factor.

Figure 3. Schematic diagram of the single-stage LED driver



The proposed circuit runs at constant peak current. The current sensing voltage is set for 1 V, which is the clamping voltage of the current sensing comparator of the L6562A. The voltage of the LED string is sensed on the INV pin of the L6562A through a coupled winding. The turn ratio of the coupled inductor is designed so that the feedback voltage is lower than 2.5 V in normal operating conditions, so the error amplifier is saturated at maximum level which sets the max. current sensing voltage to 1 V. Therefore, the peak current of the inductor is fixed at a level determined by the sensing resistor value. As the peak current of the inductor is constant, the input power is constant. The LED voltage is considered constant, and the current into the LED can also be considered constant. If the load (the LEDs) is open, the reflected output voltage on the INV pin is above a certain level, and the controller shuts down to provide open load protection.

If the inductor current is controlled at constant level all the time, then the power factor is very poor. The multiplier of the L6562A is used to reshape the current amplitude near the line voltage zero crossing to improve the power factor. The rectified sine waveform is sampled at the MULT pin. The output of the multiplier, which is the current setting, is lower than setting the level near the line voltage zero crossing. In this way, the power factor of the converter is improved significantly.

Design procedure:

- Input voltage: $Vin(\theta) = \sqrt{2} \cdot Vin \cdot \sin(\theta), Vin = 120V$
- Output voltage: 18 LEDs in series, Vout=54 V
- Output current: Iout=350 mA

The design variable is the peak current of the inductor (Ipk), and the inductance (L).

When Q1 is turned on, the inductor is charged to Ipk. The ON time is:

Equation 1

$$Ton(\theta) = \frac{L * Ipk}{Vin(t)}$$

The OFF time is:

Equation 2

$$Toff(\theta) = \frac{L * Ipk}{Vout}$$

The period of the switching cycle is:

Equation 3

$$T(\theta) = Ton(\theta) + Toff(\theta) = \frac{L * Ipk}{Vin(\theta)} + \frac{L * Ipk}{Vout}$$

The duty cycle (D) is:

Equation 4

$$D(\theta) = \frac{Ton(\theta)}{T(\theta)} = \frac{Vout}{Vout + Vin(\theta)}$$

The frequency is:

Equation 5

$$fsw(\theta) = \frac{1}{T} = \frac{1}{L * Ipk}(\frac{Vout * Vin(\theta)}{Vin(\theta) + Vout})$$

The switching frequency varies during the line cycle, which is good for EMI.

The max. frequency occurs at peak input voltage:

Equation 6

$$fsw\,max = \frac{1}{L * Ipk}(\frac{Vout * Vpk}{Vpk + Vout})$$

The input power is:

Equation 7

$$P = \int_0^{\pi} \frac{1}{2} * L * Ipk^2 * fsw(\theta)dt$$

Equation 8

$$P = \frac{1}{2} * Ipk * \int_0^{\pi} D(\theta) * Vin(\theta)d\theta$$

The integration term of *Equation 8* is a constant value, so the power is determined by Ipk only. There is no simple solution form for the integration term. The average value of the input voltage and duty cycle can be used to perform the estimation. After Ipk is calculated, the inductance can be determined according to the desired switching frequency range.

The average input voltage over half-cycle at 120 VAC line is:

Equation 9

$$Vave = \int_0^{\pi} Vpk * \sin(\theta)d\theta = 108\ \mathrm{V}$$

The average duty cycle is:

Equation 10

$$Dave = \frac{Vout}{Vave + Vout} = 0.333$$

Therefore:

Equation 11

$$Ipk = \frac{Pin}{\frac{1}{2} * Vave * Dave} = 1.2\ \mathrm{A}$$

After the current is determined, it is necessary to choose the right inductance value. The inductance affects the running frequency. The maximum switching frequency below 200 kHz has been chosen.

From *Equation 6*, we have:

Equation 12

$$L = \frac{1}{fsw\,max * Ipk}\left(\frac{Vout * Vpk}{Vpk + Vout}\right)$$

$$L = 200\,\mu H$$

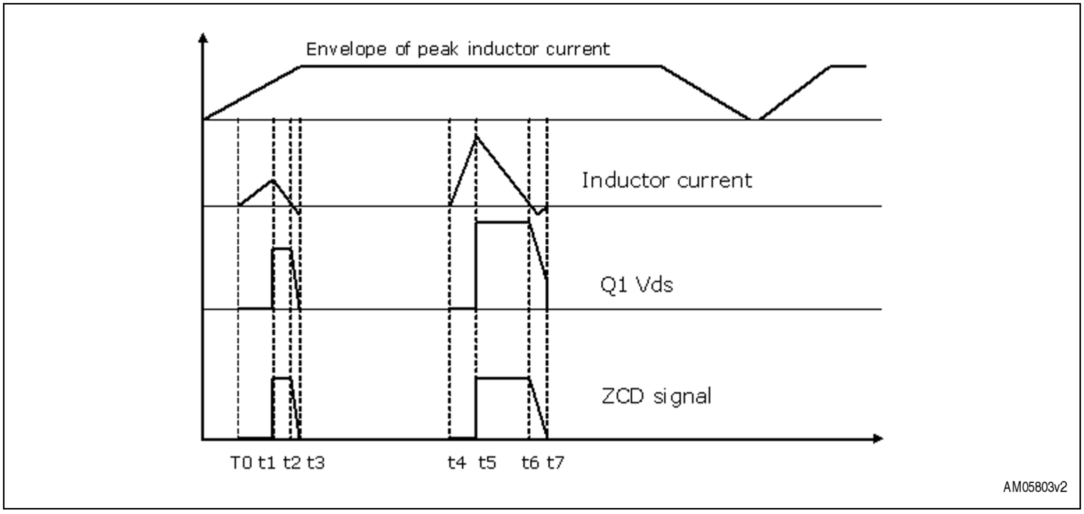
A 1 Ω current sensing resistor can be used in the application. To better handle the high current, two SMT 2 Ω resistors are implemented.

Operating principles:

The operation of the converter can be described as follows:

- The period of t0 to t3 is near the line voltage zero crossing. The period of t4 to t7 is around the peak line voltage.
- [t0,t1], Q1 is turned on at time t0. The inductor current reaches its peak at t1. Near the line voltage zero crossing, the peak amplitude is lower than the constant value Ipk.
- [t1,t2] Q1 is turned off at t1. The inductor current decreases to zero at t2.
- [t2,t3] the drain voltage of Q1 starts to fall at t2, and reaches zero at t3. The ZCD pin of the controller detects the ZCD signal low and turns on Q1 again at t3. Q1 is turned on at zero voltage.
- [t4,t5], Q1 is turned on at time t4. The inductor current reaches its peak at t4. The peak amplitude is the constant value Ipk.
- [t5,t6] Q1 is turned off at t5. The inductor current decreases to zero at t6.
- [t6,t7] the drain voltage of Q1 starts to fall at t6, and reaches its minimum value at t7, but it does not reach zero. The ZCD pin of the controller detects the ZCD signal low and turns on Q1 again at t7. Q1 is turned on at reduced voltage.

Figure 4. Illustration of key waveforms of the converter



The MOSFET Q1 operates zero voltage turn-on when the instant input voltage is lower than the output voltage. It is turned on at reduced voltage when the input voltage is higher than the output voltage. Therefore, it is a partial soft-switched converter.

The efficiency of the circuit is 88%, and the power factor is 0.85. Key waveforms are shown in the figures below.

Figure 5 shows the envelope of inductor current and input signal at the MULT pin.

Figure 5. Inductor current and multiplier input

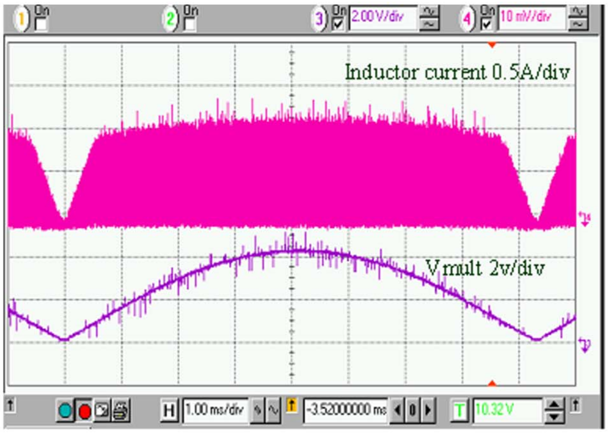


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Figure 6 shows the input voltage and current.

Figure 6. Input voltage and input current

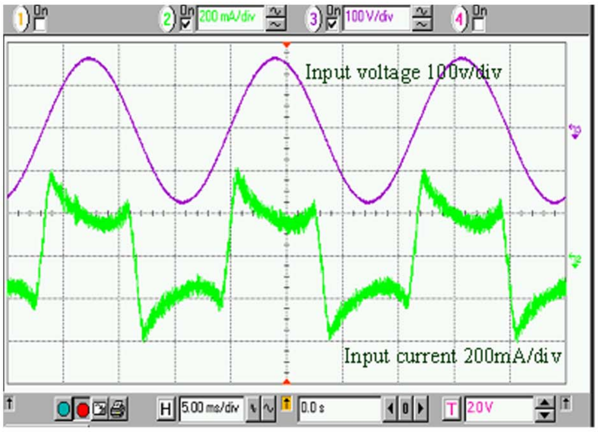

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Figure 7 shows output LED current and voltage.

Figure 7. LED voltage and LED current

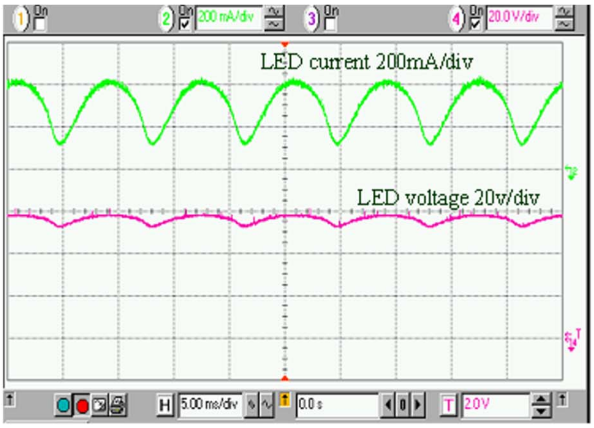

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Figure 8 and *9* show the MOSFET switching waveforms. When the input line voltage is lower than the output voltage, zero voltage turn-on is achieved. When the input voltage is higher than the output voltage, the MOSFET is turned on at reduced voltage.

Figure 8. Switching waveform of MOSFET Q1: conclusions when Vout > Vin

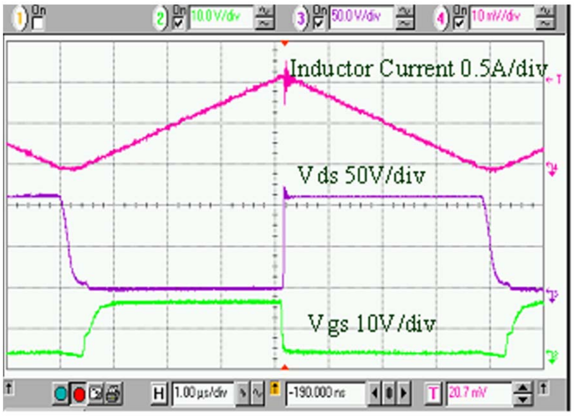

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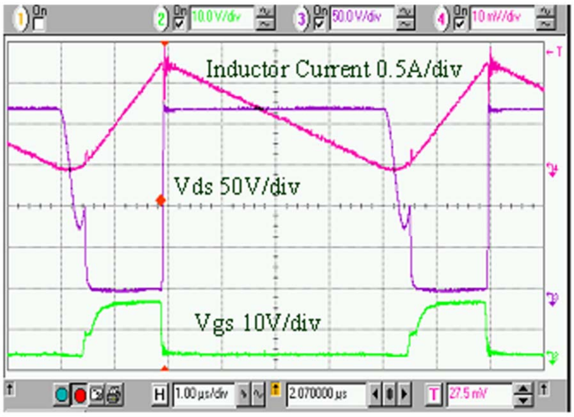
Figure 9. Switching waveform of MOSFET Q1: conclusions when Vout < Vin



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Fault conditions:

1. Open load

If the LED string is disconnected from the circuit, the output capacitor can be charged to a very high voltage if there is no overvoltage protection. The protection threshold voltage Vovp is set as 75 V. R7 and R10 sense the reflected voltage through the coupled inductor with a 4 to 1 turn ratio (N). The error amplifier of the L6562A is used to shut down the chip if overvoltage is detected.

Equation 13

$$\frac{Vovp}{N} * \frac{R10}{R7 + R10} \leq 2.5$$

2. Short-circuit

If the load is shorted, the reflected voltage is zero, and the V_{CC} of the L6562A collapses. Therefore, it is automatically protected from short-circuits. In both fault conditions, the input power is less than 0.5 W.

2 STEVAL-ILL027V1 demonstration board

Table 1. Bill of material for the STEVAL-ILL027V1

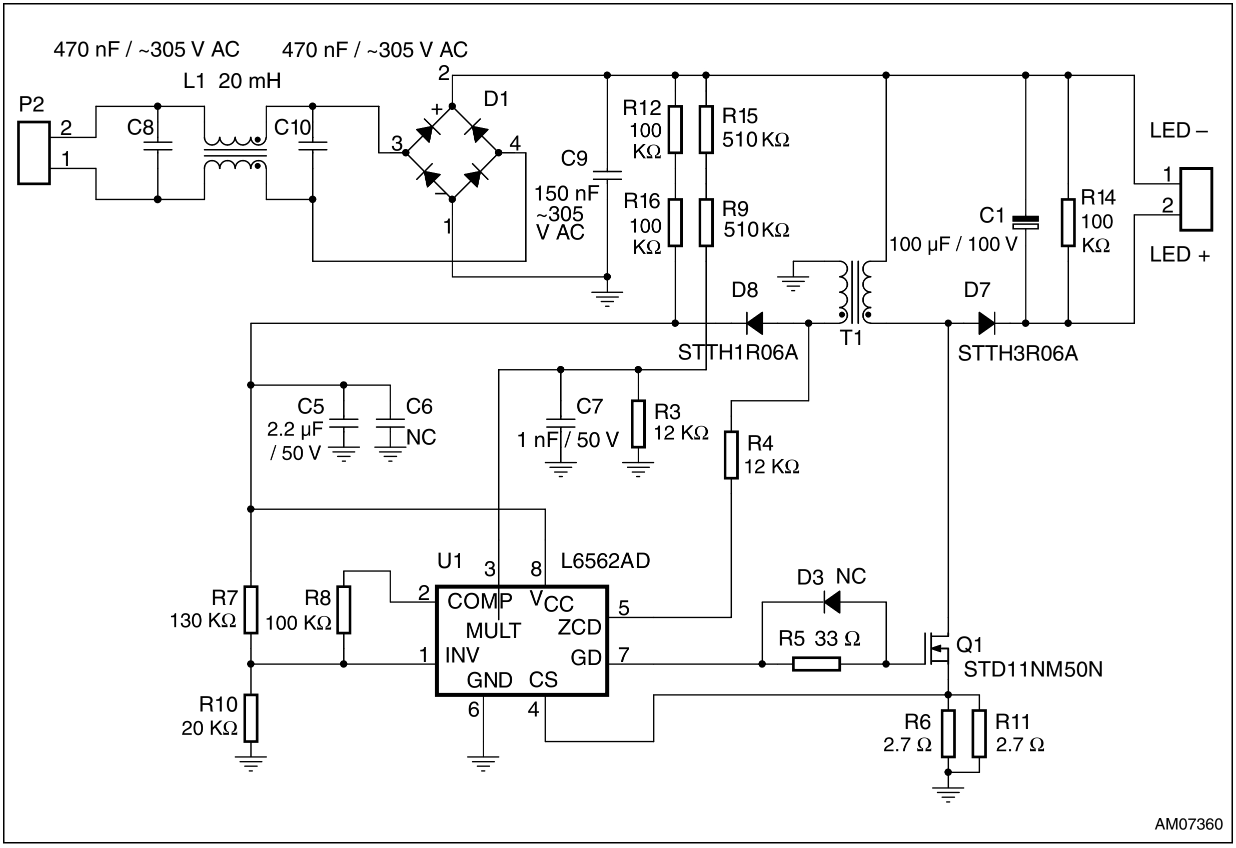
Reference	Part description / part number	Package	Manufacture
C1	82 µF / 100 V	Axial	
C5	10 µF / 35 V	SMT	
C6	0.1 µF / 50 V	805	
C7	1 nF / 50 V	805	
C8, C10	0.27 µF/250 V ECQ-E2274KF	Metal Poly.	
C9	0.68 µF/250 V ECQ-E2684KB	Metal Poly.	
D1	1 A/600 V diode bridge DF06S	SMT	
D3	1N4148WS	SMT	
D7, D8	STTH1L06A	SMA	STMicroelectronics™
L1	20 mH CM choke 744821120		Wurth Electronics Midcom
Q1	STD5NM50	DPAK	STMicroelectronics
R3	10 kΩ	805	
R4	12 kΩ	1206	
R5	100 Ω	805	
R6, R11	2 Ω	1206	
R7	130 kΩ	805	
R8	100 kΩ	805	
R14	100 kΩ	1206	
R9	510 kΩ	1206	
R10	20 kΩ	805	
R12	200 kΩ	1206	
T1	200 µH couple inductor 750310347 Rev01		Wurth Electronics Midcom
U1	L6562A	SO-8	STMicroelectronics

3 STEVAL-ILL027V2 demonstration board

An original demonstration board (STEVAL-ILL027V1) was redesigned in order to demonstrate this design concept also for the EU input voltage range. In fact, it means that the board can operate with the input voltage between 188 V and 265 V AC. The LED constant current is again set to 350 mA using the same output LED power 18 W. All required board modifications and measurements, comparing with the STEVAL-ILL027V1, are described in the following sections. The demonstration board for the EU input voltage range has the order code; STEVAL-ILL027V2.

3.1 Schematic diagram

Figure 10. STEVAL-ILL027V2 schematic diagram



3.2 BOM for the STEVAL-ILL027V2 demonstration board

Table 2. Bill of material for the STEVAL-ILL027V2

N	Q	Reference	Value	Package / class	Manufacturer	Orderable part number
1	1	C1	100 µF / 100 V	Electrolytic capacitor	Panasonic	ECA2AM101
2	1	C5	2.2 µF / 50 V	Ceramic capacitor 1210	AVX	12105C225KAT2A
3	1	C6		Not connected		
4	1	C7	1 nF / 50 V	Ceramic capacitor 1206		
5	2	C8, C10	470 nF / ~305 V AC	Foil capacitor	EPCOS	B32922C3474K
6	1	C9	150 nF / ~305 V AC	Foil capacitor	EPCOS	B32922C3154M
7	2	R3, R4	12 kΩ	Resistor 1206		
8	1	R5	33 Ω	Resistor 0805		
9	2	R6, R11	2.7 Ω	Resistor 1206		
10	1	R7	130 kΩ	Resistor 0805		
11	3	R8, R12, R16	100 kΩ	Resistor 0805		
12	2	R9, R15	510 kΩ	Resistor 1206		
13	1	R10	20 kΩ	Resistor 0805		
14	1	R14	100 kΩ	Resistor 1206		
15	1	U1	L6562AD	PFC controller	STMicroelectronics	L6562AD
16	1	Q1	STD11NM50N	Power MOSFET	STMicroelectronics	STD11NM50N
17	1	D1	1 A / 250 V	Diode bridge		
18	1	D3		Not connected		
19	1	D7	STTH3R06	Ultrafast diode	STMicroelectronics	STTH3R06S
20	1	D8	STTH1R06	Ultrafast diode	STMicroelectronics	STTH1R06A
21	1	T1		Transformer	Wurth Electronics	750310347
22	1	L1		Common mode choke	Wurth Electronics	744821120

3.3 STEVAL-ILL027V2 description for EU voltage range

This section describes all modifications done on the STEVAL-ILL027V1 in order to change the input voltage range from 120 V AC to 230 V AC. These modifications are demonstrated on the STEVAL-ILL027V2.

In order to supply the STEVAL-ILL027V2 from the EU voltage range, it is necessary to change the input foil capacitors C8, C9, and C10, because their maximum voltage is only 250 V DC (STEVAL-ILL027V1). The capacitors C8 and C10 were replaced by capacitor 470 nF / 305 V AC. Due to their size, the PCB layout was redesigned in order to fit the bigger capacitor package on the original design. The capacitors C8 and C10 470 nF / 305 V were selected, because, thanks to this value, EMI behavior is fulfilled as demonstrated in *Figure 16* and *17*. The capacitor C9 was replaced by the capacitor 150 nF / 305 V AC.

Maximum input voltage can be up to 362 V (265 V x √2) and therefore at least two SMD resistors must be used for sensing the input voltage. An additional resistor, R16 = 100 kΩ, is connected in series with R12 and the additional resistor, R15 = 510 kΩ, is connected in series with R9.

Also the voltage divider used for the MULT pin is recalculated in order to have the correct voltage on the MULT pin. The highest voltage on the MULT pin is presented for maximum input voltage 265 V AC. In this case the voltage on the MULT pin is done by the following equation:

Equation 14

$$Vmult = \frac{Vin\_max \times R3}{R3 + R9 + R15} = \frac{362 \times 12000}{12000 + 510000 + 510000} = 4.2V$$

Absolute maximum rating for the MULT pin is 8 V, which means that such a margin is high enough to correctly operate even with maximum input voltage 265 V AC.

The next modification is to change the sense resistors R6 and R11, because these resistors are used to set the level of constant LED current. The resistors R6 and R11 were replaced by resistor 2R7.

Regarding the power MOSFET capability, it is possible to calculate its maximum drain source voltage. Assume that maximum output LED voltage is approximately 72 V (18 LEDs with maximum forward voltage 4 V) and then maximum drain source voltage is:

Equation 15

$$V\_ds = Vin\_max \times \sqrt{2} + Vled\_max = 265 \times \sqrt{2} + 72 = 445V$$

For this kind of topology the switching losses are higher for higher input voltage and therefore the power MOSFET with better current capability is selected for the input voltage 230 V AC. The STD11NM50N power MOSFET is used for the STEVAL-ILL027V2 demonstration board.

Maximum reverse voltage on diode D7 is also 445 V, when the power MOSFET is ON. Ultrafast diode D7 STTH3R06A with maximum repetitive reverse voltage 600 V was selected for this application.

Electrolytic capacitor C5 = 10 µF / 35 V is replaced by the small SMD ceramic capacitor 2.2 µF / 50 V as there is a size limitation on the board.

The transformer's number of turns can be used exactly the same as on the original design, because the output LED voltage is transformed to the auxiliary winding when the MOSFET is OFF in the same ratio as on the original design. For the output LED power 18 W and constant LED current 350 mA, the LED voltage is 51.4 V. This voltage is reflected to the auxiliary winding. The transformer isolation is 500 V DC and so the transformer can be used in this application for EU input voltage range. The others components are without any change.

3.4 Measurement

Figure 11, *12* and *13* show output LED current and voltage waveforms. The LED current is slightly changed with input voltage, because it is 354 mA for 230 V, 318 mA for 180 V and 358 mA for 260 V. The LED current vs. input voltage characteristic is demonstrated in *Figure 18*.

Figure 11. Output LED current and voltage for input voltage 230 V / 50 Hz

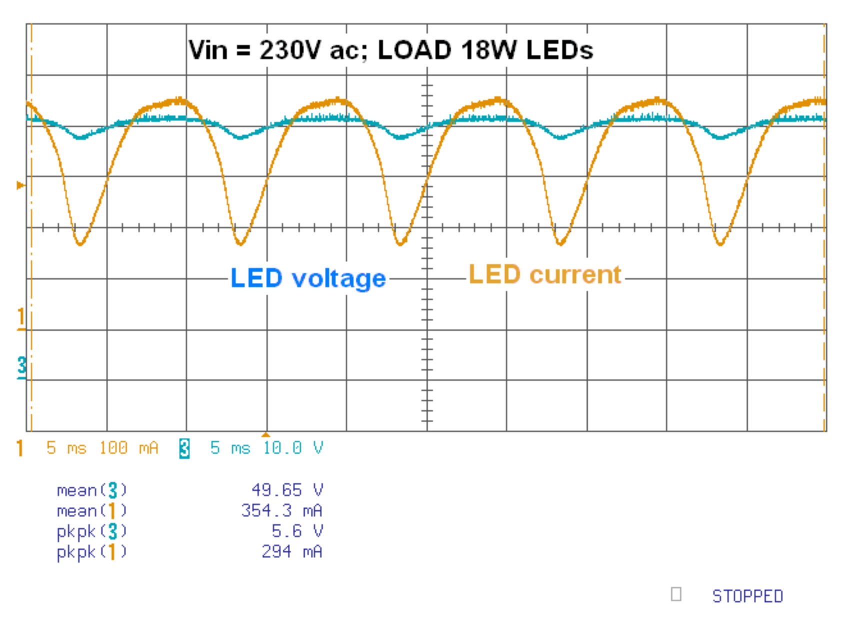


Figure 12. Output LED current and voltage for input voltage 180 V / 50 Hz

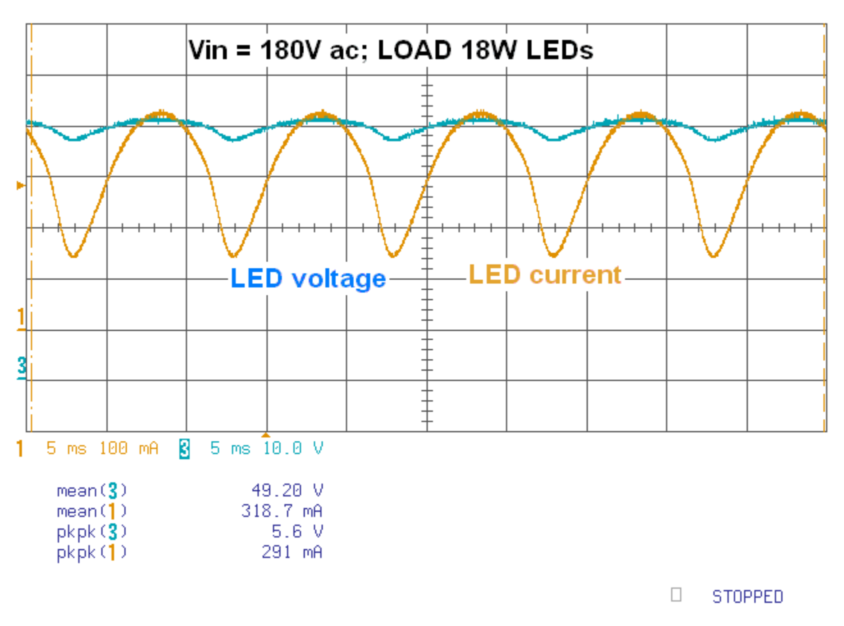
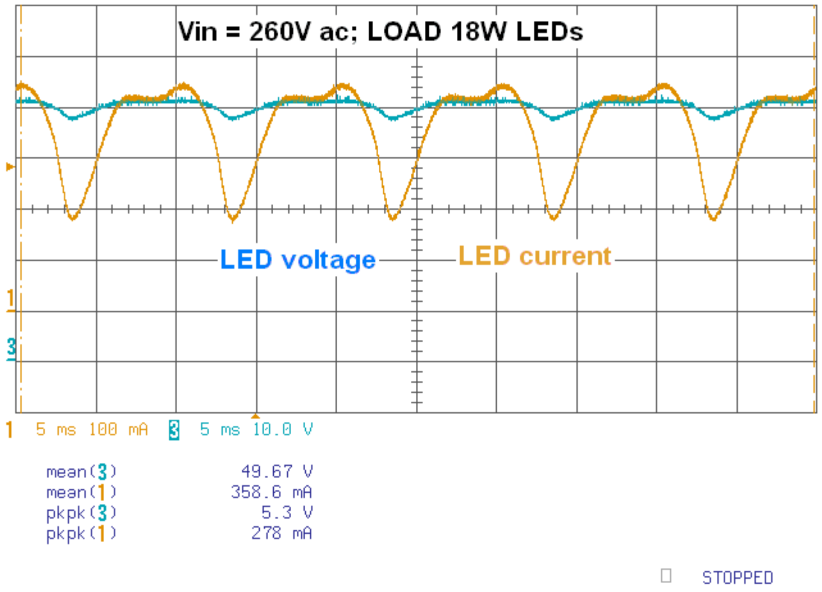


Figure 13. Output LED current and voltage for input voltage 260 V / 50 Hz



In case the output LEDs are disconnected, STEVAL-ILL027V2 has designed an open load protection. *Figure 14* shows open load protection after connecting mains voltage 230 V AC. As can be seen, output voltage is regulated to 78 V.

Figure 14. Open load measurement

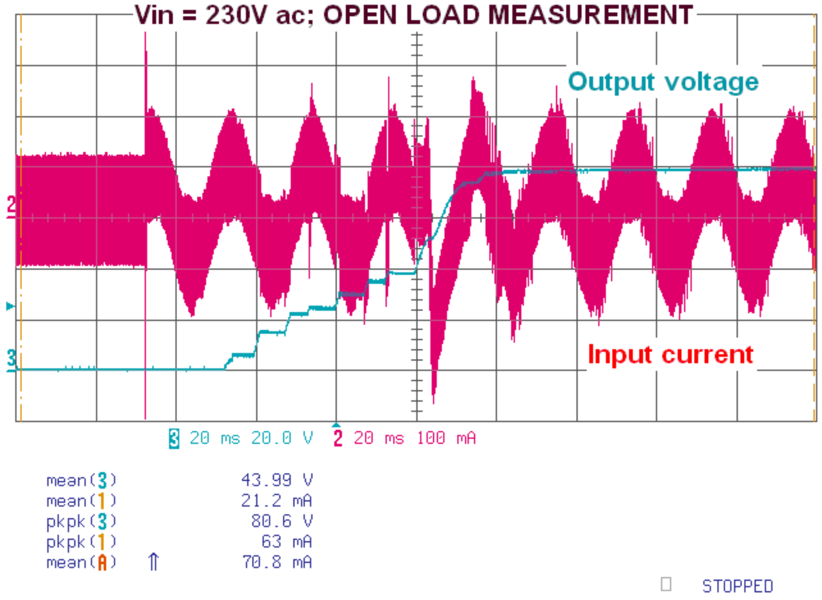
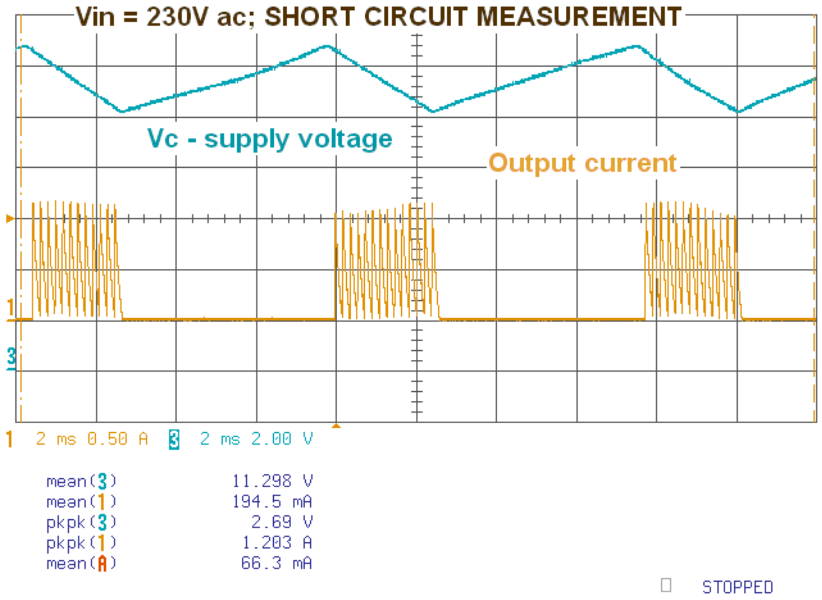


Figure 15 shows short-circuit protection. As soon as the voltage on the V_{CC} pin of the L6562A reaches the turn-on threshold (capacitor C5 is charged via resistors R12 and R16), the device starts switching (there is output current present) and the voltage V_{CC} decreases, because output voltage is almost 0 V and so the capacitor C5 cannot be supplied via the transformer from the output voltage. As soon as the voltage on the V_{CC} pin of the L6562A

reaches the turn-off threshold, the device stops switching and the capacitor C5 is again charged via resistors R12 and R16 and the cycle is repeated.

Figure 15. Short-circuit measurement



The STEVAL-ILL027V2 demonstration board is also tested for EMI behavior. The EN55015 (CISPR15) standard describes limits and methods for the measurement of radio disturbance characteristics of electrical lighting and similar equipment. STEVAL-ILL027V2 fulfills this standard, as demonstrated in *Figure 16* and *17*.

Figure 16. EMI measurement - detector average

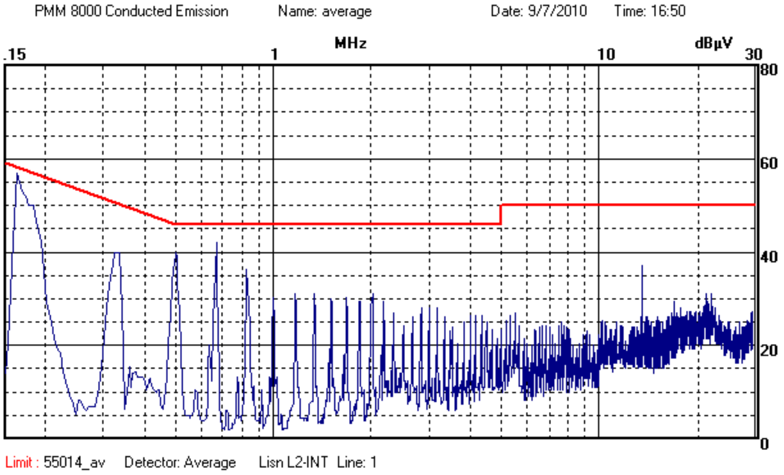


Figure 17. EMI measurement - detector quasi-peak

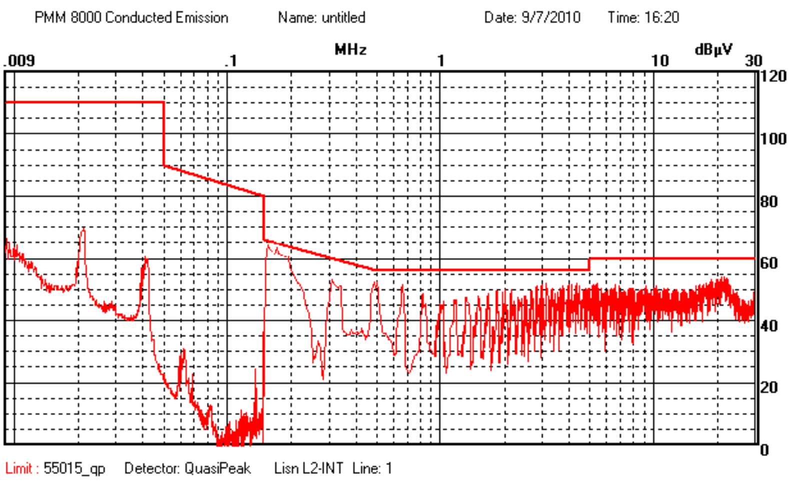


Figure 18 shows LED current for the input voltage between 180 and 260 V AC. Minimum measured LED current is 318 mA for 180 V and maximum measured LED current is 358 mA for 260 V. *Figure 19* shows efficiency for different input voltages. The efficiency is 71% for input voltage 230 V AC. *Figure 20* demonstrates LED current for a different number of LEDs connected as the load. If 15 LEDs are connected (LED forward voltage is 47 V), the LED current is 358 mA. If 19 LEDs are connected (LED forward voltage is 59 V), the LED current is 331 mA.

Figure 18. LED current vs. input voltage

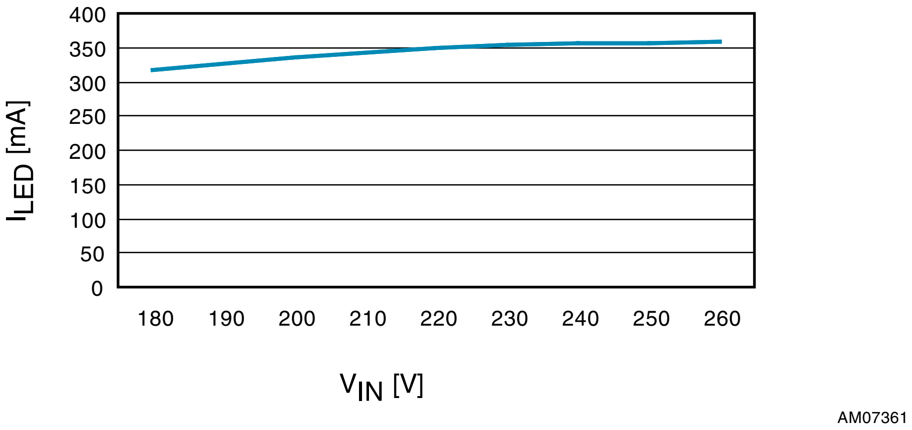


Figure 19. Efficiency vs. input voltage

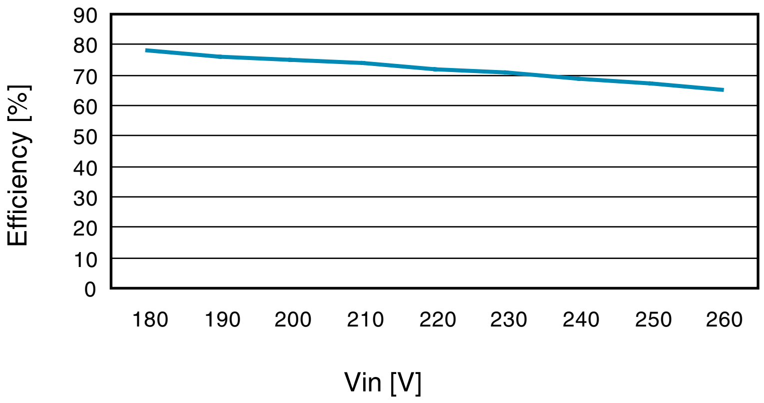


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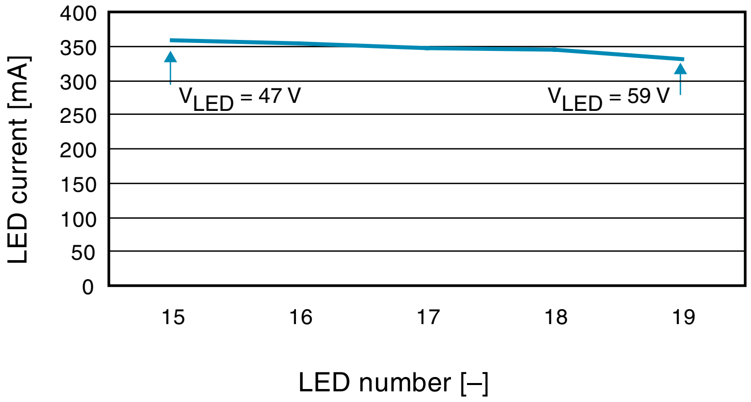
Figure 20. LED current vs. LED number



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4 Conclusion

Running at transition mode provides the benefit of lower switching losses and spread of the EMI spectrum. This buck-boost converter achieves constant power by operating at constant peak current, and high power factor is achieved by reshaping the current waveform near the zero crossing of the line voltage. This single-stage buck-boost converter provides a cost-effective solution for offline non-isolated LED applications. This single-stage LED driver has open load and short-circuit protection.

5 Reference

1. ENERGY STAR® requirements for SSL
2. AN966 application note
3. L6562A datasheet

6 Revision history

Table 3. Document revision history

Date	Revision	Changes
10-Feb-2010	1	Initial release.
08-Feb-2011	2	Corrected *Figure 4*, section “2.2 18 W single-stage offline LED driver for EU voltage range” to section “2.5 STEVAL-ILL027V1 modifications for EU voltage range” replaced by *Section 3: STEVAL-ILL027V2 demonstration board*, corrected typo in *Section 1: Circuit design* and *Section 2: STEVAL-ILL027V1 demonstration board*.

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