

# AN44

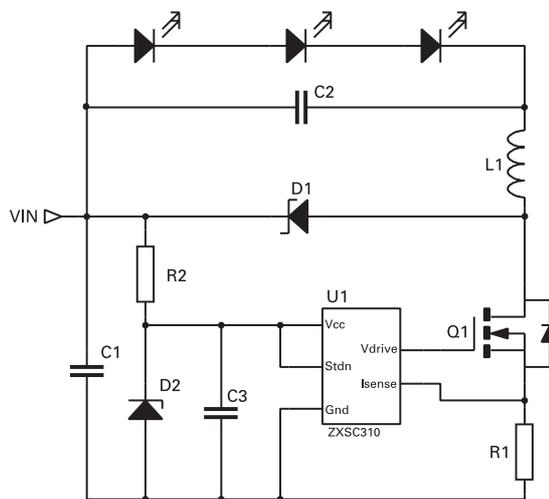
## A high power LED driver for low voltage halogen replacement

### Introduction

LED lighting is becoming more popular as a replacement technology for Halogen low voltage lighting, primarily because of the low efficiency, reliability and lifetime issues associated with Halogen bulbs.

Discussed below is a novel approach for driving high power LED's as a replacement for low voltage halogen lighting systems.

A typical schematic diagram is shown in Figure 1.



**Figure 1 Schematic diagram**

### Operation

Please refer to the typical schematic diagram in Figure 1.

#### On period, $T_{ON}$

The ZXSC300 turns on Q1 until it senses 19mV (nominal) on the  $I_{SENSE}$  pin.

The current in Q1 to reach this threshold is therefore  $19mV/R1$ , called  $I_{PEAK}$ .

With Q1 on, the current is drawn from the battery and passes through C1 and LED in parallel. Assume the LED drops a forward voltage  $V_F$ . The rest of the battery voltage will be dropped across L1 and this voltage, called  $V(L1)$  will ramp up the current in L1 at a rate  $di/dt = V(L1)/L1$ ,  $di/dt$  in Amps/sec,  $V(L1)$  in volts and L1 in Henries.

The voltage drop in Q1 and R1 should be negligible, since Q1 should have a low  $R_{DS(on)}$  and R1 always drops less than 19mV, as this is the turn-off threshold for Q1.

$$V_{IN} = V_F + V(L1)$$

$$T_{ON} = I_{PEAK} \times L1 / V(L1)$$

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So  $T_{ON}$  can be calculated, as the voltage across L1 is obtained by subtracting the forward LED voltage drop from  $V_{IN}$ . Therefore, if L1 is smaller,  $T_{ON}$  will be smaller for the same peak current  $I_{PEAK}$  and the same battery voltage  $V_{IN}$ . Note that, while the inductor current is ramping up to  $I_{PEAK}$ , the current is flowing through the LED and so the average current in the LED is the sum of the ramps during the  $T_{ON}$  ramping up period and the  $T_{OFF}$  ramping down period.

## Off period, $T_{OFF}$

The  $T_{OFF}$  of ZXSC300 and ZXSC310 is fixed internally at nominally  $1.7\mu s$ . Note that, if relying on this for current ramp calculations, the limits are  $1.2\mu s$  min.,  $3.2\mu s$  max.

In order to minimize the conductive loss and switching loss,  $T_{ON}$  should not be much smaller than  $T_{OFF}$ . Very high switching frequencies cause high  $dv/dt$  and it is recommended that the ZXSC300 and 310 are operated only up to 200 kHz. Given the fixed  $T_{OFF}$  of  $1.7\mu s$ , this gives a  $T_{ON}$  of  $(5\mu s - 1.7\mu s) = 3.3\mu s$  minimum. However, this is not an absolute limitation and these devices have been operated at 2 or 3 times this frequency, but conversion efficiency can suffer under these conditions.

During  $T_{OFF}$  the energy stored in the inductor will be transferred to the LED, with some loss in the Schottky diode. The energy stored in the inductor is:

$$\frac{1}{2} \times L \times I_{PEAK}^2 \text{ [Joules]}$$

## Continuous and discontinuous modes (and average LED current)

If  $T_{OFF}$  is exactly the time required for the current to reach zero, the average current in the LED will be  $I_{PEAK}/2$ . In practice, the current might reach zero before  $T_{OFF}$  is complete and the average current will be less because part of the cycle is spent with zero LED current. This is called the 'discontinuous' operation mode and is shown in Figure 2.

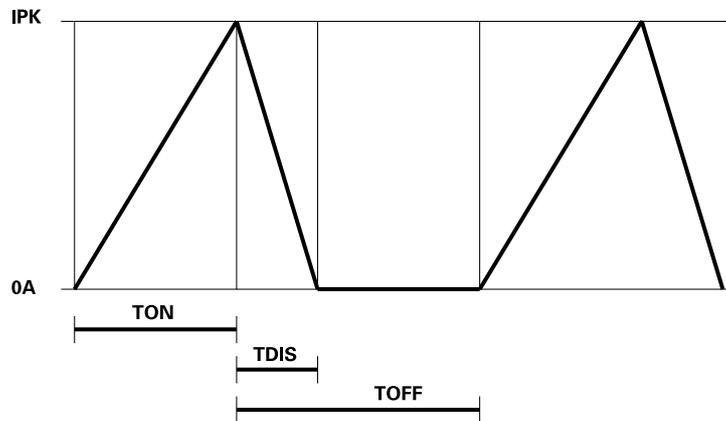


Figure 2

### For continuous mode

If the current does not reach zero after  $1.7\mu\text{s}$ , but instead falls to a value of  $I_{\text{MIN}}$ , then the device is said to be in 'continuous' mode. The LED current will ramp up and down between  $I_{\text{MIN}}$  and  $I_{\text{PEAK}}$  (probably at different  $di/dt$  rates) and the average LED current will therefore be the average of  $I_{\text{PEAK}}$  and  $I_{\text{MIN}}$ , as shown in Figure 3.

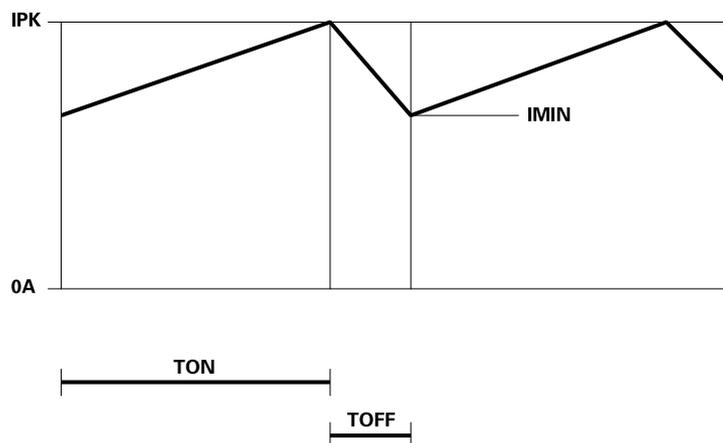


Figure 3

### Design example

(Refer to Figure 1 and Table 1)

$$\text{Input} = V_{\text{IN}} = 12\text{V}$$

$$\text{LED forward drop} = V_{\text{LED}} = 9.6\text{V}$$

$$V_{\text{IN}} = V_{\text{LED}} + V_{\text{L}}$$

$$\text{Therefore } V_{\text{L}} = (12 - 9.6) = 2.4$$

$$\text{The peak current} = V_{\text{SENSE}} / R1$$

$$(R1 \text{ is } R_{\text{SENSE}}) = 24\text{mV} / 50\text{m}\Omega = 480\text{mA}$$

$$T_{\text{ON}} = I_{\text{PEAK}} \times L1 / V(L1)$$

$$T_{\text{ON}} = \frac{680\text{mA} \times 22\mu\text{H}}{2.4} = 6.2\mu\text{s}$$

These equations make the approximation that the LED forward drop is constant throughout the current ramp. In fact it will increase with current, but they still enable design calculations to be made within the tolerances of the components used in a practical circuit. Also, the difference between  $V_{\text{IN}}$  and  $V_{\text{LED}}$  is small compared to either of them, so the  $6.2\mu\text{s}$  ramp time will be fairly dependent on these voltages.

Note that, for an LED drop of  $9.6\text{V}$  and a Schottky drop of  $300\text{mV}$ , the time to ramp down from  $680\text{mA}$  to zero would be:

$$T_{\text{DIS}} = \frac{680\text{mA} \times 22\mu\text{H}}{(9.6 + 0.3)} = 1.5\mu\text{s}$$

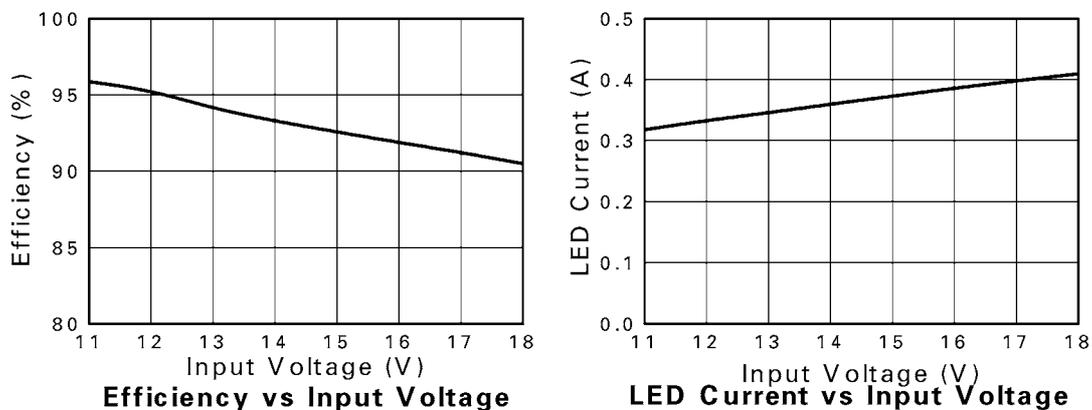
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As the  $T_{OFF}$  period is nominally  $1.7\mu s$ , the current should have time to reach zero. However,  $1.5\mu s$  is rather close to  $1.7\mu s$  and it is possible that, over component tolerances, the coil current will not reach zero, but this is not a big issue as the remaining current will be small. Note that, because of the peak current measurement and switch-off, it is not possible to get the dangerous 'inductor staircasing' which occurs in converters with fixed  $T_{ON}$  times. The current can never exceed  $I_{PEAK}$ , so even if it starts from a finite value (i.e. continuous mode) it will not exceed the  $I_{PEAK}$ . The LED current will therefore be approximately the average of  $680mA$  and zero =  $340mA$  (it will not be exactly the average, because there is a  $200ns$  period at zero current, but this is small compared with the  $I_{PEAK}$  and component tolerances).

Ref	Value	Part number	Manufacturer	Contact details	Comments
U1		ZXSC310E5	Zetex	www.zetex.com	LED Driver in SOT23-5
Q1		ZXMN6A07F	Zetex	www.zetex.com	N-channel MOSFET in SOT23
D1	1A / 40V	ZHCS1000	Zetex	www.zetex.com	1A Schottky diode in SOT23
D2	6V8	Generic	Generic		6V8 Zener diode
L1	22 $\mu$ H	DO3316P-223	Coilcraft	www.coilcraft.com	
R1	50m $\Omega$	Generic	Generic		0805 size
R2	1k2 $\Omega$	Generic	Generic		0805 size
C1	100 $\mu$ F/25V	Generic	Generic		
C2	1 $\mu$ F/10V	Generic	Generic		
C3	2.2 $\mu$ F/25V	Generic	Generic		

**Table 1 Bill of materials**

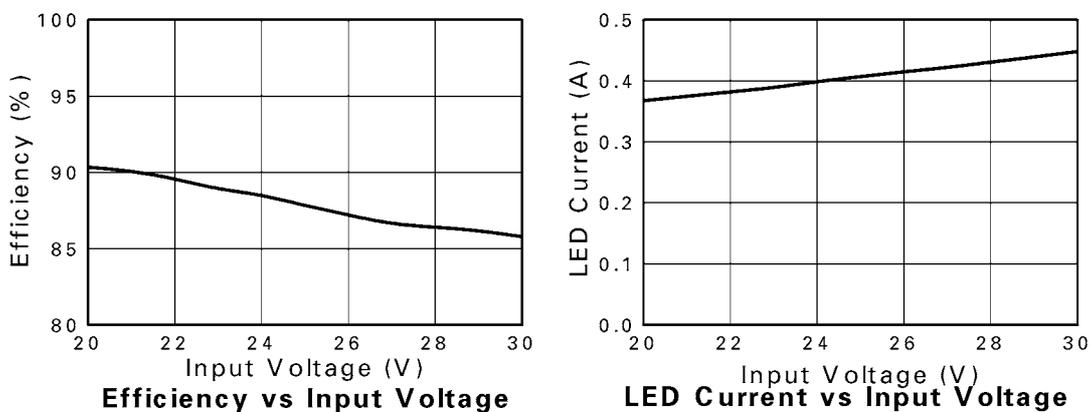
### Typical performance graphs for 12V system



**Figure 4 Performance graphs for 12V system**

By changing the value of R2 from  $1k\Omega$  to  $2k\Omega$  the operating input voltage range can be adjusted from 30V to 20V, therefore the solution is able to operate from the typical operating voltage supplies of 12V and 24V for low voltage lighting.

### Typical performance graphs for 24V system



**Figure 5 Performance graphs for 24V system**

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## Useful formulae for calculations

The input power from the battery during T<sub>ON</sub> (assuming discontinuous operation mode) is V<sub>IN</sub> \* I<sub>PEAK</sub>/2. The average input current from the battery is therefore this current multiplied by the ratio of T<sub>ON</sub> to the total cycle time:

$$\frac{I_{PEAK}}{2} \times \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

It can be seen from this how the average battery current will increase at lower V<sub>IN</sub> as T<sub>ON</sub> becomes larger compared to the fixed 1.7µs T<sub>OFF</sub>. This is logical, as the fixed (approximately) LED power will require more battery current at lower battery voltage to draw the same power.

The energy which is stored in the inductor equals the energy which is transferred from the inductor to the LED (assuming discontinuous operation) is:

$$\frac{1}{2} * L1 * I_{PEAK}^2 \text{ [Joules]}$$

$$T_{ON} = \frac{I_{PEAK} \times L1}{(V_{BATT} - V_{LED})}$$

Therefore, when the input and the output voltage difference are greater, the LED will have more energy which will be transferred from the inductor to the LED rather than be directly obtained from the battery. If the inductor size L1 and peak current I<sub>PEAK</sub> can be calculated such that the current just reaches zero in 1.7µs, then the power in the LED will not be too dependent on battery volts, since the average current in the LED will always be approximately I<sub>PEAK</sub>/2.

As the battery voltage increases, the T<sub>ON</sub> necessary to reach I<sub>PEAK</sub> will decrease, but the LED power will be substantially constant and it will just draw a battery current ramping from zero to I<sub>PEAK</sub> during T<sub>ON</sub>. At higher battery voltages, T<sub>ON</sub> will have a lower proportional of the total cycle time, so that the average battery current at higher battery voltage will be less, such that power (and efficiency) is conserved.

The forward voltage which is across the Schottky diode detracts from the efficiency. For example, assuming V<sub>F</sub> of the LED is 6V and V<sub>F</sub> of the Schottky is 0.3V, the efficiency loss of energy which is transferred from the inductor is 5%, i.e. the ratio of the Schottky forward drop to the LED forward drop. The Schottky is not in circuit during the T<sub>ON</sub> period and therefore does not cause a loss, so the overall percentage loss will depend on the ratio of the T<sub>ON</sub> and T<sub>OFF</sub> periods. For low battery voltages where T<sub>ON</sub> is a large proportion of the cycle, the Schottky loss will not be significant. The Schottky loss will also be less significant at higher LED voltages (more LED's in series) as Schottky drop becomes a lower percentage of the total voltage.

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