AND8492/D

Capacitive Drop Drive Topology with a Constant Current Regulator to Drive LEDs

ON Semiconductor

ON Semiconductor®

http://onsemi.com

APPLICATION NOTE

Abstract

This Application note describes how to properly and efficiently drive light emitting diodes (LEDs) using a Constant Current Regulator (CCR) in a capacitive drop topology, as shown below in Figure 1. The Capacitive drop topology allows for a wide range of end applications while the CCR will drive the LEDs at their optimal current to improve longevity and reliability. The LEDs themselves and the LED market is explored as a lead into the justification for this type of solution, the mathematical derivation of the various components is reviewed, concluding with four examples, 230 V_{RMS} ±6% 50 Hz, (100 to 127 V) 113.5 V $_{RMS}$ ±12% 60 Hz, 120 V_{RMS} ±5% 60 Hz and 240 V_{RMS} ± 10% 50 Hz application. This application note will use the $^+$ and $^-$ superscripts to describe the maximum and minimum values of the respective variable.

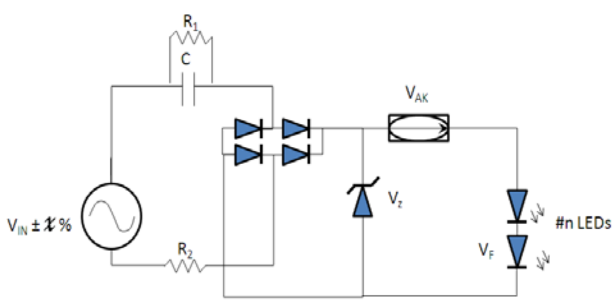

Figure 1. Capacitive Drop Topology with a CCR to Bias LEDs

Introduction

As light emitting diodes (LEDs) become more common place it is imperative to safely and effectively drive these LEDs. LEDs are diodes, the diode current has an exponential dependence on voltage. ON Semiconductor has released a line of Constant Current Regulators (CCRs) that improve efficiency and gain longevity of any end product needing a constant current.

LEDs use a combination of radiative recombination and localized well modification for recombination of electrons in the conduction band and holes in the valence band that dissipate this energy in the form of photons of a specific wavelength of light in direct band gap (i.e. III−IV compounds). As the recombination well gets thinner the energy state of the electron in the conduction band gets higher since electrons cannot be at the bottom of a well due to quantum mechanics. This is shown in Figure 2 below.

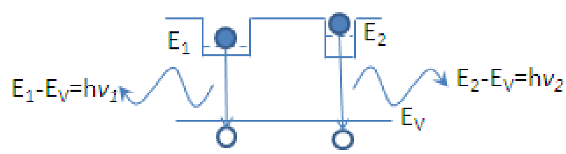

Figure 2. Two recombination zones for two different wavelengths of light

In the past lighting was achieved from using lamp filaments that give off up to 80% of their energy in the form of heat. Florescent tubes were introduced to the 1939 World’s Fair in New York City and since then have been the standard for high efficiency lighting. However florescent tubes need inefficient ballasts to ignite the gas inside the tube. These ballasts dissipate a lot energy in the form of heat. Florescent tubes contain deadly mercury which pollutes the earth, if not disposed of properly.

Everyday LEDs are improving the amount of light (lumens [lm]) they output per watt (W) of power. The US Department of Energy (February 2010 R + D Workshop) predicts that a growth from 25 to 75 lm/W in 2005 will grow to 250 lm/W by 2015, as shown in Figure 3 below.

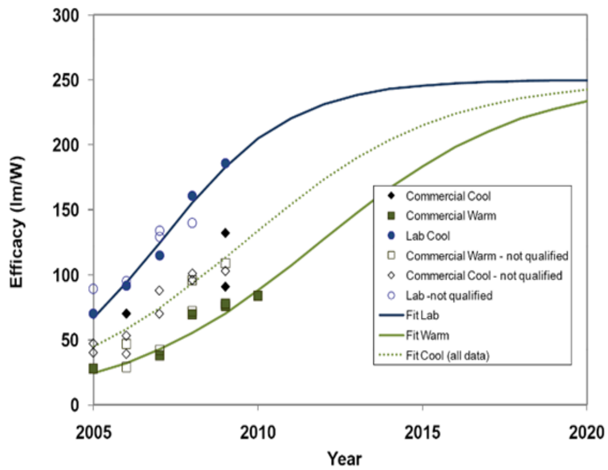

Figure 3. Warm and Cool LED Efficacy Forecast

This means that a 1 W LED in 2005 (350 mA @ 3.4 V) could put out as much light as a 0.1 W LED (35 mA @ 3.4 V) in 2015.

ON Semiconductor's Constant Current Regulator (CCR)

The CCR product portfolio ranges from 10 mA to 350 mA.

These CCRs simply limit the current of any device they are in series with. The CCR acts like a linear regulator and it absorbs fluctuations in supply voltage (up to 120 V) or change in LED forward voltage due to production or binning variations. The CCR can be used with the Capacitive Drop topology for a cost effective offline LED lighting solution. This circuit is shown in Figure 1.

To better understand how the circuit operates and how to properly size the various components, everything from the supply to the thermal and power components will be discussed.

The Supply Voltage

In many different countries not only is the "average" voltage known as the Root−Mean−Squared (RMS) voltage (V_{RMS}) supply change, but so does the tolerance ($\pm \chi$ % = $\pm \chi$/100). For example, in the United States of America the line is usually regulated to 120 V_{RMS} ± 5% 60 Hz but can range anywhere from 100 V_{RMS} to 127 V_{RMS} (Note 1). If you put the 100 to 127 V range into the $V_{RMS} \pm \chi$ % format it comes out to be 113.5 V_{RMS} ± 12%. This means that χ = 12 for this market. Recently, the European Union, and the UK, have agreed to transition from an asymmetric tolerance range (230 V +6% −10%) to 230 V_{RMS} ± 6%, 50 Hz (Note 2). To cover the worst case scenarios it is a good idea to design to the widest tolerance range, for example many people in China design to 240 V_{RMS} ±10%.

This change in RMS voltage will change the peak voltage (V_P). The supply voltage is a Sine wave signal with peaks $\sqrt{2}$ higher than the RMS voltages with a frequency (f) as shown in Equations 1 and 2. These peak voltages change with the tolerance as shown below in Equations 3 and 4.

$$V_P = V_{RMS}\sqrt{2} \qquad \text{(eq. 1)}$$

$$V_{IN} = V_P \mathrm{SIN}(2\pi f t) \qquad \text{(eq. 2)}$$

$$V_P^+ = V_{RMS} * \left(1 + \frac{x}{100}\right)\sqrt{2} \qquad \text{(eq. 3)}$$

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} \qquad \text{(eq. 4)}$$

The LEDs

LEDs need to be kept biased for current under the maximum operational current (I_{LED+}). LEDs have an exponential dependence on voltage (V_F) so it is clear that small changes in voltage create large changes in current. As seen below in Equation 5, the exponential function of the current is related to the material property (i.e. diffusion length [L_n, L_p], intrinsic carrier concentration [n_i], doping concentration [N_A, N_D]) and the physical parameters of the junction (Temperature [T] and Area[A]).

$$I_{LED}(V_F) = qAn_i^2\left(\frac{D_n}{L_n N_A} + \frac{D_P}{L_P N_D}\right)\left(e^{\frac{qV_F}{kT}} - 1\right) = I_o\left(e^{\frac{qV_F}{kT}} - 1\right) \qquad \text{(eq. 5)}$$

$$I_{LED}^+ = I_{LED}(V_F^+) = I_o\left(e^{\frac{qV_F^+}{kT}} - 1\right) \qquad \text{(eq. 6)}$$

1. ANSI C84.1−2006 American National Standard for Electrical Power Systems and Equipment.
2. CENELEC Harmonization Document HD 472 S1:1988.

For a string of "n" LEDs in series the sum of the forward voltage drops at a LED current.

$$V_{F(Total)} = \sum_{x=1}^{n} V_{F,x}(I_{LED}) \qquad \text{(eq. 7)}$$

LEDs may have variation in voltage due to binning and production ($\pm\Delta V$). Each one of these sets in series can be replaced by "m" LEDs in parallel. This will increase the current to $I_{LED(Total)}$ as shown below.

$$I_{LED(Total)} = \sum_{x=1}^{m} I_{LED,x}(V_F + \Delta V) \qquad \text{(eq. 8)}$$

If the LEDs are driven too hard by too much forward current, the LED will breakdown and permanent damage can occur, reducing lifetime and reliability. The LEDs must remain biased correctly with a constant current to ensure the LEDs remain in operation.

The CCR

As the current tries to exceed the Regulation current (I_{Reg}) of the CCR then the voltage over the CCR (V_{AK}) will increase to keep the LEDs or other devices in series with the CCR at the regulation current. Depending on the CCR the overhead voltage (V_{AK}) is near 1.8 V. To remain in very deep saturation it is recommended to bias the CCR with V_{AK} > 3 V. The general Current Voltage characteristic of the CCR is shown below in Figure 4.

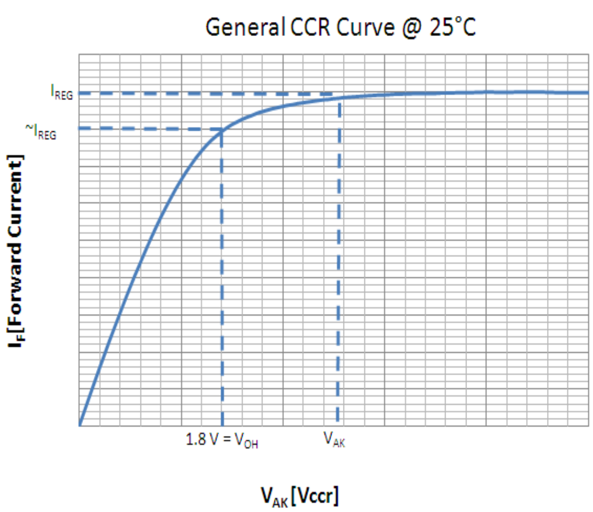

Figure 4. General CCR Current−Voltage Relationship

To best match the CCR to the LEDs it is important that the I_{Reg} is about equal to the I_{LED} rating on the LEDs in use as shown in Equation 9.

$$I_{Reg} = I^{+}_{LED} = I_{LED}(V^{+}_{F}) \qquad \text{(eq. 9)}$$

$$P_{CCR} = I_{Reg}V_{AK} \geq I_{Reg(SS)} * \left(V_Z - V_{F(Total)}\right) \qquad \text{(eq. 10)}$$

V_Z is the Zener voltage rating, discussed in "The Zeners" section later in this application note.

Traditionally the V_{AK} over the CCR is fed by the supply voltage and subtracted by forward voltage of the LEDs. In the Capacitive drop topology the user can define the V_{AK} since the coupling capacitor drops the majority of the voltage. For our examples we will set V_{AK} = 4 V.

The Coupling Capacitor

The coupling capacitor will charge both plates of the capacitor then release the charge as current phase shifted to the voltage. Equivalent AC impedance can be deduced in Equations 11 to 16.

$$V_c = \frac{1}{C}\int I_c dt \qquad \text{(eq. 11)}$$

$$i_c(t) = C\frac{dv_c(t)}{dt} \qquad \text{(eq. 12)}$$

$$v_c(t) = V_P \sin(2\pi ft) \qquad \text{(eq. 13)}$$

$$\frac{dv_c(t)}{dt} = V_P 2\pi f \cos(2\pi ft) = \frac{i_c(t)}{C} \qquad \text{(eq. 14)}$$

$$X_c = \frac{v_c(t)}{i_c(t)} = \frac{V_P \sin(2\pi ft)}{V_P 2\pi fC \sin\left(2\pi ft + \frac{\pi}{2}\right)} \qquad \text{(eq. 15)}$$

$$X_c = \frac{1}{2\pi fC} * \frac{\sin(2\pi ft)}{\sin\left(2\pi ft + \frac{\pi}{2}\right)} \qquad \text{(eq. 16)}$$

Equation 16 shows that not only will the current be scaled by the voltage but also shifted by 90° (π/2).

The Phasor section of Equation 16 only relates the time offset between the current and the voltage. Since the maximum current and voltage over each individual device is inspected the relative phase to the input voltage is irrelevant and the impedance is simplified.

To ensure there is enough charge on the capacitor to let current flow to the LEDs the capacitor should be sized so that the peak current matches the LED/CCR current at V_P^-. The X_C calculation in Equation 16 can be used to calculate the capacitor size.

$$V = IR = IX_C \qquad \text{(eq. 17)}$$

$$V_{RMS} = \frac{I_{RMS}}{2\pi fC}; V_{RMS}\sqrt{2} = \frac{I_{RMS}\sqrt{2}}{2\pi fC} \qquad \text{(eq. 18)}$$

$$V_P = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} \qquad \text{(eq. 19)}$$

$$V_P = \frac{I_{Reg}}{2\pi fC} \qquad \text{(eq. 20)}$$

$$C = \frac{I_{Reg}}{2\pi fV_P} \qquad \text{(eq. 21)}$$

Generally, when using the coupling capacitor for this type of application it is recommended that a high voltage, metal−film type capacitor is used because the high voltage the coupling capacitor could breakdown if a high voltage capacitor is not used.

Note that as the voltage rises from V_{RMS}^- to V_{RMS}^+ that the capacitor will gather extra charge on it and cause an extra supply current (ΔI). This extra current can be calculated as shown below.

$$I_P^- = I_{Reg} = 2\pi V_P^- C \quad \text{(eq. 22)}$$

$$I_P^+ = I_{Reg} + \Delta I = 2\pi V_P^+ C \quad \text{(eq. 23)}$$

$$\Delta I = 2\pi f C * \left(V_P^+ - V_P^-\right) \quad \text{(eq. 24)}$$

$$\Delta I = 2\pi f C V_{RMS}\sqrt{2} * \left(1 + + \frac{x}{100} - \left(1 - \frac{x}{100}\right)\right) \quad \text{(eq. 25)}$$

$$\Delta I = 2\pi f C V_{RMS}\sqrt{2}\,\frac{2x}{100} \quad \text{(eq. 26)}$$

$$\frac{\Delta I}{I_{Reg}} = \frac{2\pi f C V_{RMS}\sqrt{2}\,\frac{2x}{100}}{2\pi f C V_{RMS}\sqrt{2}\left(1 - \frac{x}{100}\right)} \quad \text{(eq. 27)}$$

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x} \quad \text{(eq. 28)}$$

This extra current will be discussed later in the zener section.

The Resistors

The R2 resistor acts like an inrush current control for the coupling capacitor. The R_2 is generally set to around 120 Ω just to take the edge off of the inrush current. Double check that the power through this inrush controller. By choosing the correct resistor type then this inrush controller will not be stressed.

$$P_{R2} \ge \left(I_{Reg} + \Delta I\right)^2 * 120\ \Omega \quad \text{(eq. 29)}$$

The R_1 Resistor provides a slight power factor correction and acts as safety protection feature. If the power is turned off and the capacitor is not fully discharged the PFC Resistor (R_1 across the Capacitor as shown in Figure 1) provides a discharge path. A resistor between 470 kΩ and 100 kΩ should be used as resistor R_1. As the impedance of R_1 goes to zero the effect of the coupling capacitor is lowered. Without R_1 it is equivalent to an R_1 of infinite impedance. To take into consideration the effect of R_1 the capacitor equations can be changed as follows.

$$V_{IR} = IZ \quad \text{(eq. 30)}$$

$$Z = X_C \parallel R_1 = \frac{X_C R_1}{X_C + R_1} = \frac{\frac{1}{2\pi FC} R_1}{\frac{1}{2\pi fC} + R_1} \quad \text{(eq. 31)}$$

$$Z = \frac{R_1}{2\pi f C R_1 + 1} \quad \text{(eq. 32)}$$

$$V_P^- = \frac{I_{Reg} R_1}{2\pi f C F_1 + 1} \quad \text{(eq. 33)}$$

$$C = \frac{I_{Reg} R_1 - V_P^-}{2\pi f R_1 V_P^-} \quad \text{(eq. 34)}$$

$$C = \frac{I_{Reg} R_1 - V_{RMS}\sqrt{2}\left(1 - \frac{x}{100}\right)}{2\pi f R_1 V_{RMS}\sqrt{2}\left(1 - \frac{x}{100}\right)} \quad \text{(eq. 35)}$$

As the power factor is improved by reducing R_1 the effect of the coupling capacitor will be reduced and extra leakage to the CCR+LED and Zeners will be introduced.

Note the impedance factor of the capacitor ($2\pi fC$) in Equation 28 has dropped out. This means that the changed impedance due to R_1 will also drop out as shown below in Equations 36 through 38. $2\pi fC$ turns into equivalent impedance of both the capacitor and the resistor that shows up in both the numerator and the denominator.

$$I_P^- = I_{Reg} = \frac{V_P^-\left(2\pi f C R_1 + 1\right)}{R_1} \quad \text{(eq. 36)}$$

$$I_P^+ = I_{Reg} + \Delta I = \frac{V_P^+\left(2\pi f C R_1 + 1\right)}{R_1} \quad \text{(eq. 37)}$$

$$\frac{\Delta I}{I_{Reg}} = \frac{\frac{V_{RMS}\sqrt{2}\left(2\pi f C R_1 + 1\right)}{R_1}\left(\frac{2x}{100}\right)}{\frac{V_{RMS}\sqrt{2}\left(2\pi f C R_1 + 1\right)}{R_1}\left(1 - \frac{x}{100}\right)} \quad \text{(eq. 38)}$$

Equation 38 will reduce down to Equation 28.

The Zeners (a zener diode is not necessary, but recommended)

As the voltage swings from V_P^- to V_P^+ the capacitor will gather extra charge on its plates (ΔI as shown in Equation 28). This charge cannot be dissipated through the CCR string and will gather at the Anode of the top and cathode of the bottom device of the CCR and LED string and will appear as a voltage. To make sure to not stress the devices a Zener diode is placed in parallel with the CCR and LED String. Once the CCR is in saturation ($V_{AK} > 3$ V) then the LEDs are not stressed and the zeners should turn on to dissipate the excess charge. This means that the zener voltage should be more than the LED total voltage drop and the 4 V over the CCR as shown below in Equation 39.

$$V_Z \ge V_{F(Total)} + 4\ V \quad \text{(eq. 39)}$$

It is very important to build a robust design. To ensure proper operation make sure that the zener in the correct package is selected since the power through the zener can become high.

$$P_Z \ge V_Z * \Delta I \quad \text{(eq. 40)}$$

$$P_Z \ge \left(V_{F(Total)} + 4\ V\right) * \frac{2 * I_{Reg}}{100 - x} \quad \text{(eq. 41)}$$

The Bridge

A single bridge package can be used as long as it meet the power specifications required at the total $I_{Reg} + \Delta I$ and it has an appropriate reverse blocking voltage to operate functionally for the application.

Examples

As stated previously, first an example of a 230 V_{RMS} ±6%, 50 Hz will be discussed then it will be followed by a 113.5 V_{RMS} ±12% solution. The same set of LEDs will be used to show a side by side comparison of each of the calculations and the values of the devices.

The most important equations for this circuit are the following:

Peak Voltage Equation:

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2}$$

Capacitor Value Equation:

$$C = \frac{I_{Reg}R_1 - V_P^-}{2\pi f R_1 V_P^-}$$

Peak to Regulation Current Ratio:

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x}$$

Power Through R2 Equation:

$$P_{R2} \geq \left(I_{Reg} + \Delta I\right)^2 * 120\ \Omega$$

CCR Power:

$$P_{CCR} = I_{Reg}V_{AK} \geq I_{Reg} * \left(V_Z - V_{F(Total)}\right)$$

Zener Voltage Equation:

$$V_Z \geq V_{F(Total)} + 4\ V$$

Zener Power:

$$P_Z \geq V_Z * \Delta I$$

Example #1, 230 V_{RMS} ±6%, 50 Hz

At 230 V_{RMS} ±6% it is necessary to remain LED conductivity at 230 V_{RMS} − 6%. At this sag in voltage a 305.75 V = V_P^- is reached by using Equation 4.

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} = 230\ V_{RMS}\left(1 - \frac{6}{100}\right)\sqrt{2}$$

$$V_P^- = 305.75\ V$$

A 470 kΩ Resistor will be used as R_1, a safety feature to discharge the capacitor in the off state.

For these applications 20 sets of 5, 20 mA, LEDs in parallel will be used. Each set of five LEDs in parallel LEDs consume a total of 100 mA and each set also has a V_F of 3.4 V. This gives a $V_{F(Total)}$ = 68 V. The 20 mA specification was given in the data sheet of the LEDs and the total current and voltage characteristics were calculated using Equations 7 and 8, where m = 5, n = 20.

$$V_{F(Total)} = \sum_{x=1}^{n} V_{F,x}\left(I_{LED}\right) = \sum_{x=1}^{20} 3.4\ V_F$$

$$V_{F(Total)} = 3.4\ V_F * 20 = 68\ V$$

$$I_{LED(Total)} = \sum_{x=1}^{m} I_{LED,x}\left(V_F + \Delta V\right) = \sum_{x=1}^{5} 20\ mA$$

$$I_{LED(Total)} = 20\ mA * 5 = 0.1\ A = I_{Reg}$$

To successfully get an I_{Reg} of 100 mA the NSI45090JDT4G (90 to 160 mA, DPAK) or the NSI45060JDT4G (60 to 100 mA, DPAK) can be used. This flexibility allows the customer to reduce inventory cost since they can use one product for this application in a higher or lower current application.

I_{Reg} has been chosen, it is now time to choose an appropriate coupling capacitor. By using Equation 34 and setting R_1 = 470 kΩ a 1.034 μF Capacitor is calculated.

$$C = \frac{I_{Reg}R_1 - V_P^-}{2\pi f R_1 V_P^-} = \frac{0.1\ A * 470\ k\Omega - 305.75\ V}{2\pi(50\ Hz)470\ k\Omega * 305.75\ V}$$

$$C = 1.034\ \mu F$$

Because of the ±6% variation of voltage, χ = 6, this gives a variation in current of ΔI = 0.013 A = 13 mA as calculated using Equation 28.

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x} = \frac{2 * 6}{100 - 6} = \frac{12}{94} = 0.1276$$

$$\Delta I = 0.1276 * I_{Reg} = 0.1276 * 0.1\ A = 0.013\ A = 13\ mA$$

This means that anytime there is a ±6% change in voltage there will be an additional 13% more current available at the voltage peaks. This extra current is important when finding the power for the Zeners and the inrush current suppressor (R_2). R_2 can be a 2 W, 120 Ω Resistor as calculated by Equation 29.

$$P_{R2} \geq \left(I_{Reg} + \Delta I\right)^2 * 120\ \Omega$$
$$\cong \left(0.1\ A + 0.013\ A\right)^2 * 120\ \Omega$$

$$P_{R2} \geq 1.526\ W \cong 2\ W$$

This extra current is important when selecting a zener. When the voltage dips to 230 V $_{RMS}$ −6% the current through the zener should be negligible but when the voltage rises to 230 V $_{RMS}$ +6% then the current through the zener should reach ΔI for a short bit of the cycle. The zener selected for this solution could either be two 36 V zeners (total 72 V) at 0.5 W or a single 75 V zener above 0.96 W. This being said there are two choices for zeners, either 2 of the MMSZ36 (36 V zener) or one 1SMB5946BT3G (75 V zener). Either of these zeners can be chosen so money can be saved depending on which has a lower quote rate. The 75 V zener allows for 7 V over the CCR for strong regulation current and it meets the power needs for the zener to dissipate the extra current seen because of the ±6% voltage variation. By using Equation 39 and 40 the minimum zener voltage can be found and the recommended power approximation is given.

$$V_Z \geq V_{F(Total)} + 4\text{ V} = 68\text{ V} + 4\text{ V} = 72\text{ V}$$

$$V_Z = 75\text{ V}$$

$$V_Z \geq V_Z * \Delta I = 75\text{ V} * 0.013\text{ A} \cong 0.957\text{ W}$$

Since the P_Z calculation is a DC power value a 0.957 W zener is appropriate since the total on time is a function of V_{in} and V_Z. With a slight algebraic manipulation of Equation 2 it can be stated that the total conduction time of the Zener is shown below.

$$V_{IN} = V_P \sin(2\pi ft)$$

$$V_Z = V_P \sin(2\pi f * t_1)$$

$$t_1 = \frac{\sin^{-1}\left(\frac{V_Z}{V_P}\right)}{2\pi f}$$

$$t_2 = \frac{1}{2f} - t_1$$

$$T_{ON} = 2(t_2 - t_1) = \frac{1}{f} - 4t_1$$

$$\%ON = \frac{T_{ON}}{T} = \frac{T_{ON}}{1/f} = f * T_{ON}$$

$$\%ON = 1 - \frac{2\sin^{-1}\left(\frac{V_Z}{V_P}\right)}{\pi} = 84.2\%$$

As seen in the above calculation the zeners only conduct for 84.2% of the time so the average power is 84.2% of the DC power. And 84.2% of 0.957 W is approximately 0.806 W.

Now that the zener has been selected the power over the CCR can be calculated using Equation 10.

$$P_{CCR} = I_{Reg}V_{AK} \geq I_{Reg} * \left(V_Z - V_{F(Total)}\right)$$

$$P_{CCR} = 0.1\text{ A}(75\text{ V} - 68\text{ V}) = 0.7\text{ W}$$

Since the DPAK is the package for both the NSI45060JDT4G and the NSI45090JDT4G it makes no thermal difference to differentiate between these two devices. Since the NSI45090JDT4G device has a lower slope in the $I_{Reg(SS)}$ versus R_{adj} a small change in R_{adj} due to accuracy will have a smaller effect on the $I_{Reg(SS)}$ current.

Also since the CCR is pulsed on and off and the whole objective of this design is to not stress the CCR with even a tiny pulse current over 100 mA we can look at the $I_{Reg(SS)}$ versus $I_{reg(P)}$ graph (Figure 4 in the data sheet, shown below).

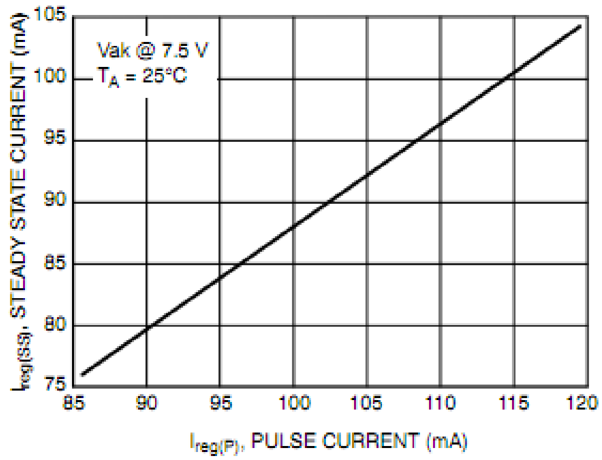

Figure 5. $I_{Reg(SS)}$ vs. $I_{Reg(P)}$

Set the LED current to the $I_{reg(P)}$ pulse current and find the corresponding steady state value. For the 100 mA LED it has a corresponding $I_{reg(SS)}$ value of approximately 87 mA. Since the device will heat up and these sharp peak currents will not be seen an approximation of 90 mA Steady state current is acceptable. Next the R_{adj} value needs to be found. To find the R_{adj} value that corresponds to the 90 mA steady state current use Figure 6: $I_{reg(SS)}$ versus R_{adj} in the datasheet shown below.

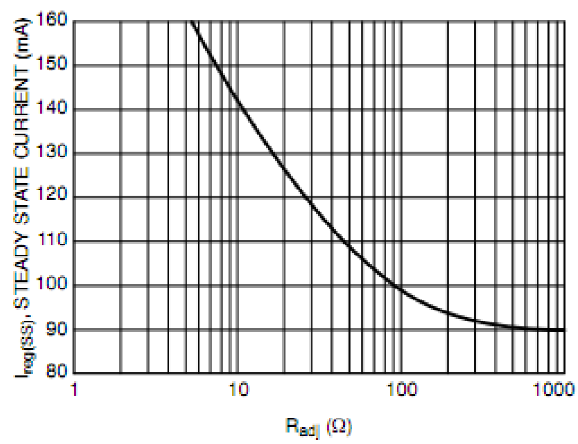

Figure 6. $I_{reg(SS)}$ vs. R_{adj}

Notice how flat the R_{adj} value is as it gets to 90mA. This means that initially the R_{adj} pin can be left open. If the overall solution gets too hot and the CCR reduced the current through the LEDs to the point where they are not being driven near 100 mA then a resistor can be added to boost the current. Since no real test can duplicate the effects of every LED tube or LED bulb it is recommended to first build a prototype then modify the R_{adj} value. The R_{adj} can be thought of as a fine tune lumen adjuster. Once the circuit is built up the R_{adj} can be adjusted to compensate for the parasitic elements in the circuit effecting lumen output.

Example #2, 113.5 V_{RMS} ±12%, 60 Hz

At 113.5 V $_{RMS}$ ±12% it is necessary to remain LED conductivity at 113.5 V_{RMS} −12%. At this sag in voltage a 141.252 V = V_P^- is reached by using Equation 4.

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} = 113.5\ V\left(1 - \frac{12}{100}\right)\sqrt{2}$$

$$V_P^- = 141.252\ V$$

A 470 kΩ Resistor will be used as R_1, a safety feature to discharge the capacitor in the off state.

For these applications 20 sets of 5, 20 mA, LEDs in parallel will be used. Each set of 5 LEDs in parallel LEDs consume a total of 100 mA and each set also has a VF of 3.4 V. This gives a $V_{F(Total)}$ = 68 V. The 20 mA specification was given in the data sheet of the LEDs and the total current and voltage characteristics were calculated using Equations 7 and 8, where m = 5, n = 20.

$$V_{F(Total)} = \sum_{x=1}^{n} V_{F,x}(I_{LED}) = \sum_{x=1}^{20} 3.4\ V_F$$

$$V_{F(Total)} = 3.4\ V_F * 20 = 68\ V$$

$$I_{LED(Total)} = \sum_{x=1}^{m} I_{LED,x}(V_F + \Delta V) = \sum_{x=1}^{5} 20\ mA$$

$$I_{LED(Total)} = 20\ mA * 5 = 0.1\ A = I_{Reg}$$

To successfully get an I_{Reg} of 100 mA the NSI45090JDT4G or the NSI45060JDT4G can be used. This flexibility allows the customer to reduce inventory cost since they can use one product for this application in a higher or lower current application.

I_{Reg} has been chosen, it is now time to choose an appropriate coupling capacitor. By using Equation 34 and setting R_1 = 470 kΩ a 1.87 μF Capacitor is calculated.

$$C = \frac{I_{Reg}R_1 - V_P^-}{2\pi f R_1 V_P^-} = \frac{0.1\ A - 470\ k\Omega - 141.252\ V}{2\pi(60\ Hz)470\ k\Omega * 141.252\ V}$$

$$C = 1.87\ \mu F$$

Because of the ±12% variation of voltage, $\mathcal{X}$ = 12, this gives a variation in current of ΔI = 0.0273 A = 27.3 mA as calculated using Equation 28.

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x} = \frac{2 * 12}{100 - 12} = \frac{24}{88} = 0.2727$$

$$\Delta I = 0.273 * I_{Reg} = 0.273 * 0.1\ A = 0.0273\ A$$
$$= 27.3\ mA$$

This means that anytime there is a ±12% change in voltage there will be an additional 27% more current available at the voltage peaks. This extra current is important when finding the power for the Zeners and the inrush current suppresser (R_2). R_2 can be a 2 W, 120 Ω Resistor as calculated by Equation 29.

$$P_{R2} \geq \left(I_{Reg} + \Delta I\right)^2 * 120\ \Omega$$
$$\cong \left(0.1\ A + 0.0273\ A\right)^2 * 120\ \Omega$$

$$P_{R2} = 1.94\ W \cong 2\ W$$

This extra current is important when selecting a zener. When the voltage dips to 113 V_{RMS} − 12% the current through the zener should be negligible but when the voltage rises to 113 V_{RMS} + 12% then the current through the zener should reach ΔI for a short bit of the cycle. The zener selected for this solution is a single 75 V, 3 W zener. A 1SMB5946BT3G is more than sufficient. The 75 V zener allows for 7 V over the CCR for strong regulation current and it meets the power needs for the zener to dissipate the extra current seen because of the ±12% voltage variation. By using Equation 39 and 40 the minimum zener voltage can be found and the recommended power approximation is given.

$$V_Z \geq V_{F(Total)} + 4\ V = 68\ V + 4\ V = 72\ V$$

$$V_Z = 75\ V$$

$$P_Z \geq V_Z * \Delta I = 75\ V * 0.0273\ A \cong 2.045\ W$$

Since the P_Z calculation is a DC power value a 2.045 W zener is appropriate since the total on time is a function of V_{in} and V_Z. With a slight algebraic manipulation of Equation 2 it can be stated that the total conduction time of the Zener is shown below.

$$V_{IN} = V_P \sin(2\pi ft)$$

$$V_Z = V_P^- \sin\left(2\pi f * t_1\right)$$

$$t_1 = \frac{\sin^{-1}\left(\frac{V_Z}{V_P^-}\right)}{2\pi f}$$

$$t_2 = \frac{1}{2f} - t_1$$

$$T_{ON} = 2\left(t_2 - t_1\right) = \frac{1}{f} - 4t_1$$

$$\%ON = \frac{T_{ON}}{T} = \frac{T_{ON}}{1/f} = f * T_{ON}$$

$$\%ON = 1 - \frac{2\sin^{-1}\left(\frac{V_Z}{V_P}\right)}{\pi} = 84.2\%$$

As seen in the above calculation the zeners only conduct for 80% of the time so the average power is 64.4% of the DC power. And 64.4% of 2.045 W is approximately 1.316 W.

Now that the Zener has been selected the power over the CCR can be calculated using Equation 10.

$$P_{CCR} = I_{Reg}V_{AK} \geq I_{Reg} * \left(V_Z - V_{F(Total)}\right)$$

$$P_{CCR} = 0.1\ A\left(75\ V - 68\ V\right) = 0.7\ W$$

Since the DPAK is the package for both the NSI45060JDT4G and the NSI45090JDT4G it makes no thermal difference to differentiate between these two devices. Since the NSI45090JDT4G device has a lower slope in the $I_{Reg(SS)}$ versus R_{adj} a small change in R_{adj} due to accuracy will have a smaller effect on the $I_{Reg(SS)}$ current.

Also since the CCR is pulsed on and off and the whole objective of this design is to not stress the CCR with even a tiny pulse current over 100 mA we can look at the $I_{Reg(SS)}$ versus $I_{reg(P)}$ graph (Figure 4 in the data sheet, shown below).

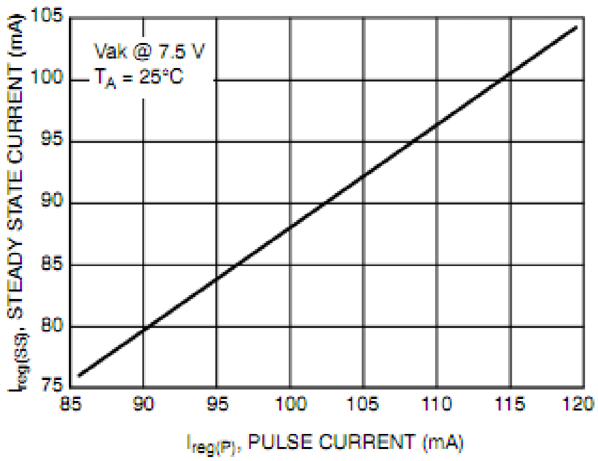

Figure 7. $I_{Reg(SS)}$ vs. $I_{Reg(P)}$

Set the LED current to the $I_{reg(P)}$ pulse current and find the corresponding steady state value. For the 100 mA LED it has a corresponding $I_{reg(SS)}$ value of approximately 87 mA. Since the device will heat up and these sharp peak currents will not be seen an approximation of 90 mA Steady state current is acceptable. Next the R_{adj} value needs to be found. To find the R_{adj} value that corresponds to the 90 mA steady state current use Figure 6: $I_{reg(SS)}$ versus R_{adj} in the datasheet shown below.

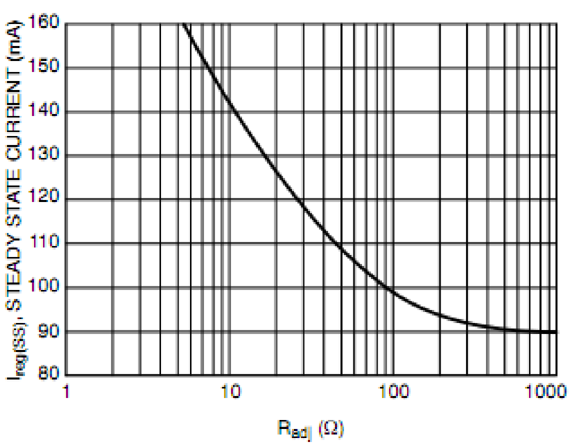

Figure 8.

Notice how flat the R_{adj} value is as it gets to 90 mA. This means that initially the R_{adj} pin can be left open. If the overall solution gets too hot and the CCR reduced the current through the LEDs to the point where they are not being driven near 100mA then a resistor can be added to boost the current. Since no real test can duplicate the effects of every LED tube or LED bulb it is recommended to first build a prototype then modify the R_{adj} value. The R_{adj} can be thought of as a fine tune lumen adjuster. Once the circuit is built up the R_{adj} can be adjusted to compensate for the parasitic elements in the circuit effecting lumen output.

Since a complete walk−through has been done for two situations a fast calibration of the Capacitor, P_{R2}, and P_Z will be discussed for the other two examples (120 V_{RMS} ± 5%, and 240 V_{RMS} ± 10%).

Example #3, 120 V_{RMS} ±5%, 60 Hz

If the same LEDs are used the $V_{F(Total)}$, $I_{LED(Total)}$, CCR selection, P_{CCR}, R_1 and R_2 remain the same as in the previous examples.

$$V_{F(Total)} = 68\text{ V}$$

$$I_{LED(Total)} = 0.1\text{ A}$$

$$CCR = NSI45090JDT4G$$

$$P_{CCR} = 0.7\text{ W}$$

$$R_1 = 470\text{ k}\Omega$$

$$R_2 = 120\ \Omega$$

$$P_{CCR} = 0.7\text{ W}$$

At 120 V $_{RMS}$ ±5% it is necessary to remain LED conductivity at 120 V $_{RMS}$ −5%. At this sag in voltage a 161.22 V = V_P^- is reached by using Eq 4.

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} = 120\text{ V}\left(1 - \frac{5}{100}\right)\sqrt{2}$$

$$V_P^- = 161.22\text{ V}$$

By using equation 34 and setting R_1 = 470 kΩ a 1.64 uF Capacitor is calculated.

$$C = \frac{I_{Reg}R_1 - V_P^-}{2\pi f R_1 V_P^-} = \frac{0.1\text{ A} * 470\text{ k}\Omega - 161.22\text{ V}}{2\pi(60\text{ Hz})470\text{ k}\Omega * 161.22\text{ V}}$$

$$C = 1.64\ \mu\text{F}$$

Because of the ±5% variation of voltage, χ = 5, this gives a variation in current of ΔI = 0.0105 A = 10.5 mA as calculated using Equation 28.

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x} = \frac{2 * 5}{100 - 5} = \frac{10}{95} = 0.105$$

$$\Delta I = 0.105 * I_{Reg} = 0.105 * 0.1\text{ A} = 0.0105\text{ A}$$
$$= 10.5\text{ mA}$$

This means that anytime there is a ±5% change in voltage there will be an additional 10.5 % more current available at the voltage peaks. This extra current is important when finding the power for the Zeners and the inrush current suppresser (R_2). R_2 can be a 1.5 W to 2 W, 120 Ω Resistor as calculated by Equation 29.

$$P_{R2} \geq \left(I_{Reg} + \Delta I\right) * 120\ \Omega$$

$$\cong (0.1\ A + 0.0105\ A)^2 * 120\ \Omega$$

$$P_{R2} \geq 1.46\ W \cong 1.5\ W$$

This extra current is important when selecting a zener. When the voltage dips to 120 V_{RMS} −5% the current through the zener should be negligible but when the voltage rises to 120 V_{RMS} +5% then the current through the zener should reach ΔI for a short bit of the cycle. The zener selected for this solution is a single 75 V, 3 W zener. A 1SMB5946BT3G is more than sufficient. The 75 V zener allows for 7 V over the CCR for strong regulation current and it meets the power needs for the zener to dissipate the extra current seen because of the ±5% voltage variation. By using equation 39 and 40 the minimum zener voltage can be found and the recommended power approximation is given.

$$V_Z \geq V_{F(Total)} + 4\ V = 68\ V + 4\ V = 72\ V$$

$$V_Z = 75\ V$$

$$P_Z \geq V_Z * \Delta I = 75\ V * 0.0105\ A \cong 0.789\ W$$

Since the P_Z calculation is a DC power value a 0.789 W zener is appropriate since the total on time is a function of V_{in} and V_Z. With a slight algebraic manipulation of Equation 2 it can be stated that the total conduction time of the Zener

$$\%ON = 1 - \frac{2\sin^{-1}\left(\frac{V_Z}{V_P}\right)}{\pi} = 69.2\%$$

As seen in the above calculation the zeners only conduct for 69.2% of the time so the average power is 69.2% of the DC power. And 69.2% of 0.789 W is approximately 0.546 W.

Example #4, 240 V_{RMS} ±10%, 50 Hz

If the same LEDs are used the $V_{F(Total)}$, $I_{LED(Total)}$, CCR selection, P_{CCR}, R_1 and R_2 remain the same as in the previous examples.

$$V_{F(Total)} = 68\ V$$

$$I_{LED(Total)} = 0.1\ A$$

$$CCR = NSI45090JDT4G$$

$$P_{CCR} = 0.7\ W$$

$$R_1 = 470\ k\Omega$$

$$R_2 = 120\ \Omega$$

At 240 V $_{RMS}$ ±10% it is necessary to remain LED conductivity at 240 V_{RMS} −10%. At this sag in voltage a 305.47 V = V_P^- is reached by using Eq 4.

$$V_P^- = V_{RMS} * \left(1 - \frac{x}{100}\right)\sqrt{2} = 240\ V\left(1 - \frac{10}{100}\right)\sqrt{2}$$

$$V_P^- = 305.47\ V$$

By using equation 34 and setting R_1 = 470 kΩ a 1.035 uF Capacitor is calculated.

$$C = \frac{I_{Reg}R_1 - V_P^-}{2\pi f R_1 V_P^-} = \frac{0.1\ A * 470\ k\Omega - 305.47\ V}{2\pi(50\ Hz)470\ k\Omega * 305.47\ V}$$

$$C = 1.035\ \mu F$$

Because of the ±10% variation of voltage, χ = 10, this gives a variation in current of ΔI = 0.022 A = 22 mA as calculated using Equation 28.

$$\frac{\Delta I}{I_{Reg}} = \frac{2x}{100 - x} = \frac{2 * 5}{100 - 10} = \frac{20}{90} = 0.22$$

$$\Delta I = 0.22 * I_{Reg} = 0.22 * 0.1\ A = 0.022\ A = 22\ mA$$

This means that anytime there is a ±10% change in voltage there will be an additional 22% more current available at the voltage peaks. This extra current is important when finding the power for the Zeners and the inrush current suppresser (R_2). R_2 can be a 2 W, 120 Ω Resistor as calculated by Equation 29.

$$P_{R2} \geq \left(I_{Reg} + \Delta I\right) * 120\ \Omega$$

$$\cong (0.1\ A + 0.022\ A)^2 * 120\ \Omega$$

$$P_{R2} \geq 1.786\ W \cong 2\ W$$

This extra current is important when selecting a zener. When the voltage dips to 240 V $_{RMS}$ −10% the current through the zener should be negligible but when the voltage rises to 240 V_{RMS} + 10% then the current through the zener should reach ΔI for a short bit of the cycle. The zener selected for this solution is a single 75 V, 3 W zener. A 1SMB5946BT3G is more than sufficient. The 75 V zener allows for 7 V over the CCR for strong regulation current and it meets the power needs for the zener to dissipate the extra current seen because of the ±10% voltage variation. By using equation 39 and 40 the minimum zener voltage can be found and the recommended power approximation is given.

$$V_Z \geq V_{F(Total)} + 4\ V = 68\ V + 4\ V = 72\ V$$

$$V_Z = 75\ V$$

$$P_Z \geq V_Z * \Delta I = 75\ V * 0.22\ A \cong 1.65\ W$$

Since the P_Z calculation is a DC power value a 1.65 W zener is appropriate since the total on time is a function of V_{in} and V_Z. With a slight algebraic manipulation of Equation 2 it can be stated that the total conduction time of the Zener is;

$$\%ON = 1 - \frac{2\sin^{-1}\left(\frac{V_Z}{V_P}\right)}{\pi} = 84.2\%$$

As seen in the above calculation the zeners only conduct for 84.2% of the time so the average power is 84.2% of the DC power. And 84.2% of 1.65 W is approximately 1.39 W.

Conclusion

The Capacitive drop topology changes swings in voltage to swings in current. Using a constant current regulator to regulate the LED string current allows smaller forward voltage LEDs to be driven at higher voltages with large swings. For voltages swings less than 45 V the application note AND8433/D should be considered.

LIST OF CCRs

Product	VI Max (V)	IO Max (mA)	Package Type
NSIC2020B	120	20	SMB−2
NSIC2030B	120	30	SMB−2
NSIC2050B	120	50	SMB−2
NSI45015W	45	15	SOD−123
NSI45020	45	20	SOD−123
NSI45020A	45	20	SOD−123
NSI45025	45	25	SOD−123
NSI45025A	45	25	SOD−123
NSI45025AZ	45	25	SOT−223−4 / TO−261−4
NSI45025Z	45	25	SOT−223−4 / TO−261−4
NSI45030	45	30	SOD−123
NSI45030A	45	30	SOD−123
NSI45030AZ	45	30	SOT−223−4 / TO−261−4
NSI45030Z	45	30	SOT−223−4 / TO−261−4
NSI45020J	45	20 to 40	SOT−223−4 / TO−261−4
NSI45035J	45	35 to 70	SOT−223−4 / TO−261−4
NSI45060JD	45	60 to 100	DPAK−3
NSI45090JD	45	90 to 160	DPAK−3
NSI50150AD	50	150 to 350	DPAK−3
NSI50010YT1G	50	10	SOD−123
NSI50350AD	50	350	DPAK−3
NSI50350AS	50	350	SMC−2

PUBLICATION ORDERING INFORMATION

LITERATURE FULFILLMENT:
Literature Distribution Center for ON Semiconductor
P.O. Box 5163, Denver, Colorado 80217 USA
Phone: 303−675−2175 or 800−344−3860 Toll Free USA/Canada
Fax: 303−675−2176 or 800−344−3867 Toll Free USA/Canada
Email: orderlit@onsemi.com

N. American Technical Support: 800−282−9855 Toll Free USA/Canada
Europe, Middle East and Africa Technical Support:
Phone: 421 33 790 2910
Japan Customer Focus Center
Phone: 81−3−5817−1050

ON Semiconductor Website: **www.onsemi.com**

Order Literature: http://www.onsemi.com/orderlit

For additional information, please contact your local Sales Representative