

## Optimizing CCR Protection for Minimal Part Count



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### APPLICATION NOTE

#### Introduction

Overvoltage protection (OVP) must be carefully considered in direct-AC applications where low LED load voltages are used. Specifically, direct-AC applications require inventive uses of OVP because the driver must reconcile the large voltage difference between the bridge and the LED load.

At the same time, space constraints are a practical design force in nearly all LED driver systems today. Physical and economic constraints alike continually reduce the size of driver designs and other supporting components. In these scenarios, space-optimized, low part-count solutions become highly desirable.

This technical note presents simple and intuitive in-driver OVP techniques for ON Semiconductor Constant Current Regulator (CCR) devices, offering schematics using a minimum of parts, and providing necessary design equations as support. Some system-level implications of these circuits were briefly touched on in the application note AND9179/D, but will be explored to much greater depth here in this note.

This document will first propose a solution schematic, review CCR device limitations, overview the operation of

multiple solutions, explore relevant design criteria, and finally end with a few design examples, complete with bills of materials.

#### Solution Schematic

Figure 1 below shows an OVP technique using two CCRs and two Zener diodes. The intuition here is that rated CCRs have nearly the same current values, so they may be placed in series with one another to effectively double the voltage breakdown of the current regulating circuitry, seen by the rest of the circuit. Just as adding CCRs in parallel increases the current, using CCRs in series conceivably increases the total breakdown voltage.

Using the constant-current, variable-voltage CCR in conjunction with a variable-current, constant-voltage Zener diode yields a sort of complete self-regulating CCCV driver. This scheme is especially useful for guarding against voltage peaks beyond the voltage breakdown rating of one CCR, but less than twice the rating. The Zener diodes are simply connected in parallel with the CCRs, which limits the number of nodes, reduces board space, and simplifies PCB layout.

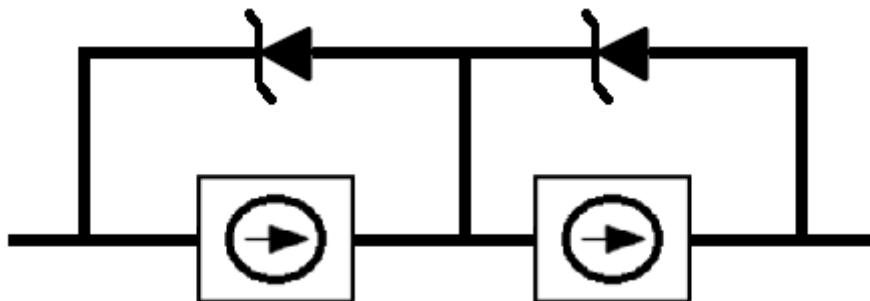


Figure 1. CCR OVP scheme utilizing two identical CCRs and two parallel zeners.

## AND9203/D

### Device Limitations

The breakdown voltage and rated current conditions of all CCRs are listed below. Table 1 lists the device names, along with the voltage breakdowns, rated current values, and

current tolerance (% , mA) ratings. All three of these specifications must be accounted for when designing Zener-based overvoltage protection schemes for CCRs.

**Table 1. CCR Voltage Breakdown and Nominal/Tolerance Current Ratings**

Device Name	V <sub>AK</sub> Max	Rated Current	Tolerance (%)	Tolerance (mA)
NSI50010YT1G	50 V	10 mA	± 30 %	± 3 mA
NSI45015WT1G	45 V	15 mA	± 20 %	± 3 mA
NSIC2020JBT3G	120 V	20 mA	± 15 %	± 3 mA
NSI45020T1G	45 V	20 mA	± 15 %	± 3 mA
NSI45020AT1G	45 V	20 mA	± 10 %	± 2 mA
NSI45020JZT1G	45 V	20 – 40 mA	± 15 %	± 3 – 6 mA
NSI45025T1G, NSI45025ZT1G	45 V	25 mA	± 15 %	± 3.75 mA
NSI45025AT1G, NSI45025AZT1G	45 V	25 mA	± 10 %	± 2.5 mA
NSIC2030JBT3G	120 V	30 mA	± 15 %	± 4.5 mA
NSI45030T1G, NSI45030ZT1G	45 V	30 mA	± 15 %	± 4.5 mA
NSI45030AT1G, NSI45030AZT1G	45 V	30 mA	± 10 %	± 3 mA
NSI45035JZT1G	45 V	35 – 70 mA	± 15 %	± 5.25 – 10.5 mA
NSIC2050JBT3G	120 V	50 mA	± 15 %	± 7.5 mA
NSI45060JDT4G	45 V	60 – 100 mA	± 15 %	± 9 – 15 mA
NSI45090JDT4G	45 V	90 – 160 mA	± 15 %	± 13.5 – 24 mA
NSI50150ADT4G	50 V	150 – 350 mA	± 15 %	± 22.5 – 52.5 mA
NSI50350AST3G, NSI50350ADT4G	50 V	350 mA	± 10 %	± 35 mA

### Solution Operation

Current levels are usually established by the application—the end user’s choice of CCR is determined by application specifications, such as output power level or desired RMS current. Occasionally, voltage limitations are set on the CCR too, which may influence the design (or necessity, even) of OVP on the drivers themselves. With enough voltage headroom, or for the extra insurance, dual CCRs may be employed as an increased voltage buffer to current-regulate a load.

More than likely, in a practical case at least some mismatch will exist between CCRs used in series. In this event, one of the Zeners acts as a parallel shunt path for extra current (see Figures 2a and 2b). Each CCR regulates at its natural operating points, and once active, the Zener diode will be able to reconcile any differences in operating points between the CCRs. Designing the Zeners to handle CCR mismatch is critical for proper operation and reliability when implementing this OVP technique.

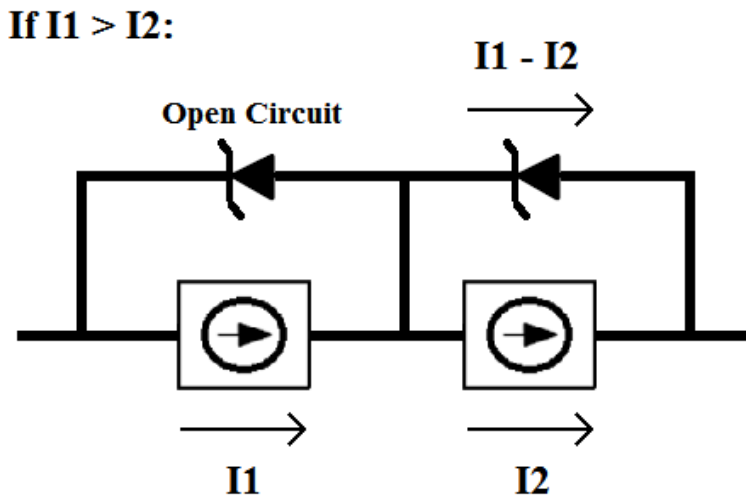


Figure 2. (a): CCR OVP generic practical scheme involving mismatch. The Zener in parallel with the highest current CCR is typically an open circuit.

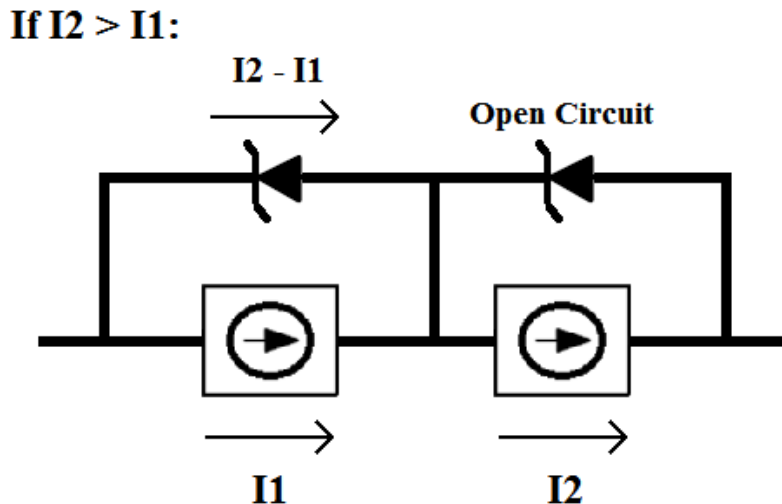


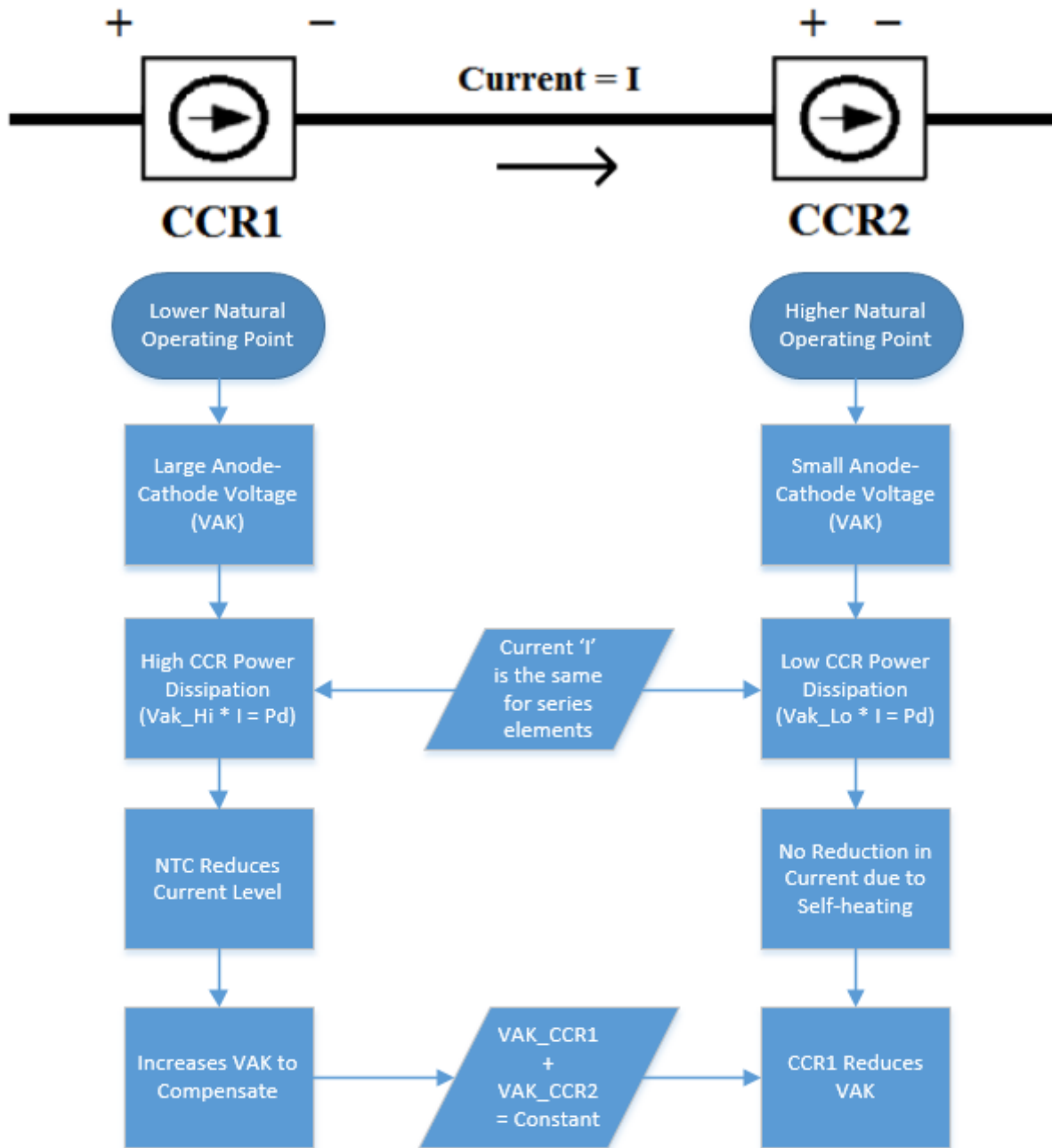
Figure 2. (b): CCR OVP generic practical scheme involving mismatch. The Zener in parallel with the highest current CCR is typically an open circuit.

Given the apparent “one on, one off” status of the Zeners pictured in Figure 2, it appears natural to question the necessity of one (or both) voltage regulators.

If Zener diodes are not used to voltage-regulate mismatched CCRs (as in Figure 3), then the current level is clamped to the lower current CCR’s operating point, causing an excessively large voltage drop, when compared to the smaller drop on the higher current CCR. This action actually causes a positive-feedback loop, wherein the negative temperature coefficient (NTC) of the lower current CCR begins to reduce the current as power dissipation (voltage drop times current) increases, creating an even greater voltage drop on the lower current device, which self-perpetuates until the CCR reaches voltage breakdown or the part burns out.

This process is illustrated in Figure 3, but can be avoided by co-regulating the voltage drops on the CCRs, using such techniques as pictured in Figure 2.

Therefore, when not voltage-regulating the CCRs, the total current through the system is equal to the current of the lowest CCR, and the system risks being unstable. Conversely, when voltage-regulating the CCRs (using Zener diodes, principally), current through the activated shunt Zener is equal to the difference in CCR currents (see (Eq. 4) which nets an overall higher current level, as well as introducing a mechanism to control thermal runaway. This performance is vastly superior and more predictable than not using Zener voltage protection at all.



**Figure 3. When used as OVP without parallel Zeners, CCRs enter a positive feedback loop that reduces reliability and system lifetime.**

Still, other configurations exist that can further reduce the number of Zeners, obtaining other driver behaviors. For example, the configuration shown in Figure 4 lends the user more control over the power dissipation and current level, and eliminates one of the Zener diodes present in the schematics of Figures 1 and 2. By using one Zener in parallel with a lower current CCR (CCR1), and then connecting an intentionally higher current CCR in series (CCR2), the one Zener is guaranteed to be the only active shunt path in the

circuit. The user must either use a higher-rated CCR or take other steps (such as utilize Radj-functionality) to ensure that the un-shunted CCR has the greater current value. The schematic may also be switched around—the higher current CCR can come first in the series string, followed by the lower current CCR and Zener. The order of placement does not matter so long as the elements are in series, and thereby can regulate current.

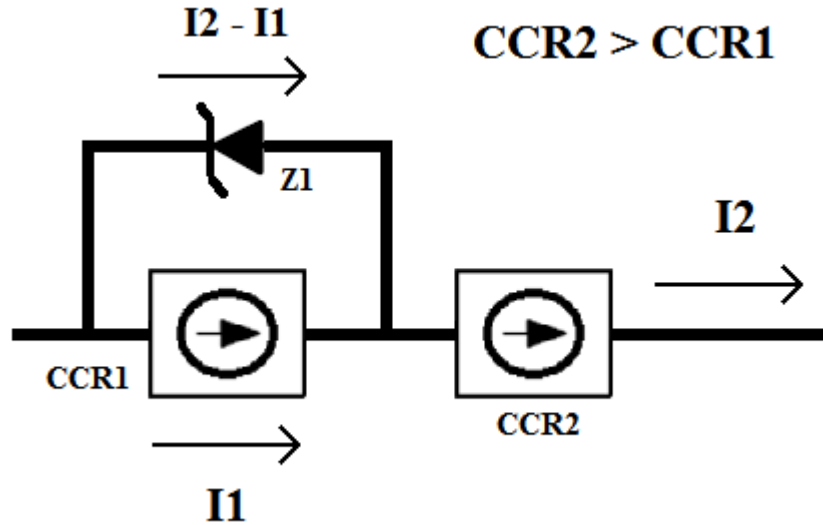


Figure 4. OVP scheme pairing an intentionally higher current CCR (CCR2) and lower current CCR (CCR1), with a Zener diode as a shunt current path.

In low-voltage scenarios, CCR1 drops most of the voltage (until the Zener voltage is reached), Z1 is open, and CCR2 drops very little voltage due to the low operating point, and the current conducted is controlled by the lower value CCR1.

Once the Zener voltage is surpassed on CCR1, then Z1 becomes available as a shunt path, able to conduct the difference between CCR2 and CCR1. At this point, the current level through the whole system increases, as CCR2 begins the new current-limiting device (recall CCR2's current level is greater than CCR1's), and Z1 starts to dissipate power. Additionally, if CCR2 is a resistor-adjustable (Radj) device, the user has very fine control over the current level through the LEDs when using a tuning resistor.

So long as the Zener is chosen appropriately (properly accounting for its own power dissipation, while also setting the power dissipation of CCR1), the circuit is safe to run in steady state, operating in either current level.

A particular benefit of this two-level current stepping is that in direct-AC applications, the voltage-dependent step obtains extremely good harmonics and THD, and may be considered as a type of linear PFC technique. This effect is present in the dual Zener topology as well, but is more exaggerated in this case because the CCR values are intentionally different.

**Design Criteria**

As seen in Figure 1, the voltage drop across the CCR and its corresponding Zener will be identical, since they are connected in parallel. If one of the Zeners turns on, the CCR is subjected to that Zener voltage for the duration of the on-time—the voltage drop on the CCR will not exceed the zener voltage for any reason. For this reason, Zener voltages should be less than the CCR maximum anode-cathode

( $V_{AK}$ ) voltage breakdown rating to prevent damaging the CCRs. However, to receive the benefit of extending the total  $V_{AK}$  rating, the sum of the Zener voltages must be equal at least the original CCR  $V_{AK}$ , otherwise nothing (other than extra power dissipation) is gained with the extra circuitry.

$$V_{AK,max} > V_Z > 0.5 \cdot V_{AK,max} \quad (\text{eq. 1})$$

Another point to consider is that the Zeners themselves do not regulate current, a CCR must remain in operation for the total current to be regulated. For this reason, the sum of the zener voltages (indicated by  $V_{Z1}$  and  $V_{Z2}$  in Eq. 2) must be greater than the total anticipated voltage drop on both CCRs, so that only one zener is ever activated at any given time and the CCR controls the total current.

$$V_{Z1} + V_{Z2} > V_{CCRs,max} \quad (\text{eq. 2})$$

In some special cases, half of the maximum  $V_{AK}$  may still be unreasonable power dissipation for the CCR. Some high current linear drivers need to be carefully checked for power dissipation on the driver itself before an inappropriately high Zener voltage is forced over it. In these cases, the only limit on  $V_Z$  is an upper bound, derived from the power rating of the CCR, shown by Eq. 3.

$$V_Z < \frac{P_{diss}}{I_{reg}} \quad (\text{eq. 3})$$

As previously mentioned, the total current through the system is determined by the CCR with the highest nominal current, with the Zener shunt current being defined as the difference in CCR current levels, shown in Eq. 4.

$$I_Z = CCR_{HI} - CCR_{LO} \quad (\text{eq. 4})$$

The CCR currents are well within the tolerance ratings given for each device (shown in Table 1), so these will be used in Zener design and selection.

The absolute worst-case scenario to be considered in Zener selection is the case where the CCRs lie at the tolerance range extremes, as identified in Eq.5 below:

$$I_{Z,max} = CCR_{Tol}(max) - CCR_{Tol}(min) \quad (eq. 5)$$

$$= CCR_{Nom} \cdot (Tol_{Max} - Tol_{Min})$$

Alternatively, the worst-case Zener current may be written as a function of rated nominal CCR current and tolerance maximum and minimums:

$$I_{Z,max} = CCR_{Nom} \cdot (Tol_{Max} - Tol_{Min}) \quad (eq. 6)$$

$$= 2 \cdot CCR_{Nom} \cdot Tol_{Max}$$

When operating in a direct-AC environment, conduction time plays into the final Zener power dissipation. In a DC environment, the Zener may be expected to be always conducting, yielding a duty cycle equal to 1. But with the rising and falling bridge voltages of direct-AC, the zener will conduct only in a small window of time, which impacts the power level relevant in Zener selection. The window that the Zener conducts in is dependent on the sum of the Zener voltage and load voltage, and that sum's relationship to the total supply voltage. Using peak values, this can be calculated fairly easily with trigonometry. The formula for duty cycle conduction for a Zener diode is given by Eq.7:

$$D = \frac{2}{\pi} \cdot \cos^{-1}\left(\frac{V_F + V_Z}{V_{pk}}\right) \quad (eq. 7)$$

Typical values for D range from 0.3 to 0.6, depending on the LED forward voltage, Zener voltage, and even mains characteristics. As usual, worst-case mains conditions should be considered.

The Zener voltage, maximum Zener current, and anticipated duty cycle determine the power rating of the Zener diode used, shown in Eq. 8.

$$P_Z = V_Z \cdot I_{Z,max} \cdot D \quad (eq. 8)$$

With a voltage value remotely set by the CCR breakdown, and a power rating determined by the application's current level and conduction duty cycle, selecting an appropriate Zener diode becomes very straight forward.

**Design Examples**

The following examples are presented as scenarios where CCR/Zener protection techniques would be beneficial. The cases are detailed in full, including load, CCR, and mains specifications, along with the design processes and equations, and suggested Zener diodes as solutions.

**Example 1) 220 V<sub>AC</sub>, 30 mA LED load**

In this case, we consider a driver consisting of two identical CCRs (NSIC2030JBT3G) in series with an LED load (referred to commonly as the "straight circuit"). For the purposes of this calculation, let's assume a ± 10 % tolerance on the nominal 220 V<sub>AC</sub> mains voltage. Thus, we have a worst-case maximum peak voltage of roughly 340 V.

$$220 V_{AC} \cdot 1.1 \cdot \sqrt{2} = 340 V_{pk}$$

Given perhaps an LED load of 160 V, this leaves about 180 V to be dropped over the current regulator. Clearly beyond the 120 V maximum of any CCR, OVP must be used to ensure the driver works under all possible conditions. Recalling that each zener must break over below the CCR breakdown point (120 V, according to Eq. 1), and that the sum of the Zener voltages must exceed the anticipated voltage drop on the CCRs (180 V, as determined in this problem, and according to Eq. 2), we conclude that Zeners between 95 and 110 V<sub>Z</sub> are appropriate for this application. Let's use 100 V<sub>Z</sub> for this example. From these values, using Eq. 7, we obtain a duty cycle (D) of:

$$D = \frac{2}{\pi} \cdot \cos^{-1}\left(\frac{160 + 100}{340}\right) = 0.44$$

To determine the power rating of the Zeners, we consider the worst-case current, derived from the tolerance of the CCRs. The CCR tolerance is ± 15 %, or ± 4.5 mA — a 9 mA difference, worst-case. The worst-case power dissipation on the Zener then, is found by Eq. 8:

$$100 V_Z \cdot 9 mA \cdot 0.44 = 0.396 W = 396 mW$$

With this information, we can determine that an 1SMB5949B (100 V, 3.0 W, SMB) or an MMSZ5272BT1G (110 V, 0.5 W, SOD-123) would make an excellent fit for this application. If desired, the user may split the voltage dropped over successive smaller Zeners too, such as using two MMSZ5262BT1G (51 V, 0.5 W, SOD-123) Zeners in series—this has the same end result, but with half the power dissipation on each device.

**Example 2) 120 V<sub>AC</sub>, 90 mA LED load**

In this case, we consider a driver consisting of the schematic shown in Figures 1 and 2, with two Zeners and two CCRs. In this scenario, let us conceive of a 90 mA, 112 V<sub>F</sub> LED load. 90 mA is difficult to achieve with few 120 V CCRs (minimum of three must be used in parallel), so to reduce part count, we utilize two 45 V, 90 mA CCRs in series (conceivably the NSI45090JDT4G), with necessary protection devices in place.

Worst-case peak voltage (assuming ± 10 % mains tolerance) for 120 V<sub>AC</sub> mains may be calculated according to the following:

$$120 V_{AC} \cdot 1.1 \cdot \sqrt{2} = 186 V_{AC}$$

Using 112 V<sub>F</sub> LEDs, this leaves 74 V, worst-case to be dropped on the regulators combined. Since the sum of the Zener voltages must be greater than the maximum drop on the CCRs (according to Eq. 2), while individually being less than the max V<sub>AK</sub> breakdown of the CCR (according to Eq. 1), which is 45 V for the NSI45090JDT4G. For these reasons, we will select 39 V<sub>Z</sub> Zeners for this application.

$$V_{Z1} + V_{Z2} > 72 V$$

$$V_{Z1} = V_{Z2} < 45 V$$

Because perfect matching between CCRs is improbable, the Zeners are designed to handle the worst-case current differences, calculated by Eq. 6 below:

$$I_{Z,max} = 90 \text{ mA} \cdot (2 \cdot 15\%) = 27 \text{ mA}$$

In a direct-AC application, the Zener is active while the bridge voltage is high, and off while the bridge is low, reducing the power dissipation significantly. This effective “duty cycle” may be found Eq. 7, and is shown below:

$$D = \frac{2}{\pi} \cdot \cos^{-1}\left(\frac{160 + 100}{340}\right) = 0.38$$

Now it is possible to calculate the worst-case power dissipation for either Zener, using Eq. 8.

$$P_Z = 39 \text{ V}_Z \cdot 27 \text{ mA} \cdot I_Z \cdot 0.38 = 0.42 \text{ W}$$

For this power rating, an appropriate choice for zener would be the 1SMA5939B (39 V, 1.5 W, SMA) for small heat sinking, or the MMSZ5259BT1G (39 V<sub>Z</sub>, 0.5 W, SOD-123).

### Example 3) 120 V<sub>AC</sub>, Alternate Schematic, 70 mA LED load

In this case, we consider a driver consisting of the alternative schematic (Figure 4), using an Radj CCR NSI45060JDT4G (45 V, 60+ mA, DPAK), and using an NSIC2050JBT3G (50 mA, 120 V, SMB) in parallel with a Zener.

Recall the peak voltage calculation from Case 2, where the peak voltage was found to be 186 V<sub>pk</sub>. Driving a standard 54 V<sub>F</sub> LED load, this leaves 132 V to be dropped across the current regulators. Since this is greater than the voltage breakdown of any CCR, we must use OVP to ensure circuit reliability.

The Zener voltage problem is a bit different in this case, since the CCRs have different maximum V<sub>AK</sub> ratings. The NSIC2050JBT3G has a 120 V breakdown, and the NSI45060JDT4G has a 45 V breakdown. The zener voltage is required to be below the breakdown of the parallel CCR (Eq. 1), in this case, the 120 V. Let's choose a 91 V<sub>Z</sub> Zener diode in this case, which leaves a maximum drop of 41 V on the 60 mA CCR.

$$132 \text{ V}_{\text{drop}} - 91 \text{ V}_Z = 41 \text{ V}_{\text{CCR}}$$

The worst-case current through the Zener diode is determined by Eq. 5, calculation shown below:

$$\begin{aligned} I_{Z,max} &= \text{CCR}_{\text{max}} - \text{CCR}_{\text{min}} \\ &= 69 \text{ mA} - 42.5 \text{ mA} = 26.5 \text{ mA} \end{aligned} \quad (\text{eq. 9})$$

Given a voltage peak of 186 V, an LED V<sub>F</sub> of 54 V, and a Zener voltage of 91 V, by Eq. 7 we calculated a duty cycle D of 0.43, yielding a total power dissipation (using Eq. 8) of:

$$P_Z = V_Z \cdot I_Z \cdot D = 91 \text{ V} \cdot 26.5 \text{ mA} \cdot 0.43$$

$$P_Z = 1.04 \text{ W}$$

For this power rating, an appropriate choice of Zener diode would be the 1SMB5948B (91 V, 3.0 W, SMB), or possibly the series sum of smaller Zeners.


### Conclusion

Using only a minimum of additional parts, it is possible to enhance the effective voltage breakdown of CCR-based LED drivers. The functional benefits are critical to direct-AC, linear driver applications, where voltage dropped on your regulator is significant. As well, space is a practical design factor, and reducing PCB costs and circuit complexity are desirable outcomes of driver design.

ON Semiconductor Constant Current Regulators are a simple and robust LED driver platform that, like any other LED driver, have limited operating conditions, such as voltage breakdown and driver power dissipation. However, there are numerous circuit configurations that address these limitations, and using only a minimum of parts, it is possible to enhance the value and performance of the drivers to the rest of the system.

### References

- [1] AND9179/D, “In-Driver High Voltage Protection Techniques for Constant Current Regulators,” ON Semiconductor.  
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