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AND9179/D

In-Driver Voltage Protection Techniques for Constant Current Regulators

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APPLICATION NOTE

Introduction

Linear LED drivers protect load elements, such as LEDs, from dangerous high−current conditions. However, these drivers themselves possess limits of their own, particularly regarding excessive voltage stimuli. Inherently, linear LED drivers require a voltage drop to drive a load.

When placed in series with an LED load, at least one terminal of the LED driver is voltage−regulated due to the LEDs. If not carefully considered, LED load design may leave linear drivers at risk of overvoltage scenarios. In these cases, it becomes necessary to implement protection schemes to ensure device stability and reliability, while also maintaining overall driver integrity and desirable performance.

These solutions distinguish themselves from circuit−level over−voltage protection (OVP) techniques, such as using a metal−oxide varistor (MOV), to protect against power line surges. The solutions in this technical note explore in−driver techniques to prevent CCRs from exceeding their voltage ratings while enduring normal power line conditions.

This document will begin with a review of ON Semiconductor Constant Current Regulator (CCR) device limitations, discuss violating circuit conditions, and end with an overview of the most effective OVP topologies to protect CCRs from high−voltage stimuli.

Conceptual Schematic

Figure 1 conceptualizes the CCR as a current−regulating block, which will be regarded behaviorally throughout this application note. Over−voltage protection (OVP) must be deployed in series with the CCR in order to displace voltage dropped off the regulator device.

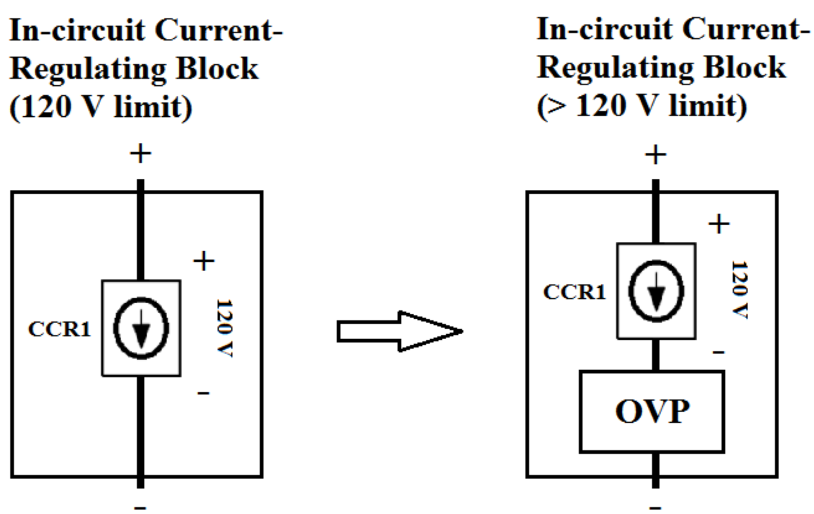

Figure 1. CCR and Protection Circuitry Visualized as High−level Current Regulating Blocks

CCR Maximum Ratings

The breakdown voltage of a CCR may be discerned from the fourth and fifth characters in any CCR device’s name. Table 1 below lists the three options and lists sample part numbers for each option. Note that not all current levels come in every voltage breakdown option. For example, all resistor−adjustable have 45 V − 50 V breakdowns. 120 V breakdown devices are well−suited for offline direct−AC applications.

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Table 1. ALL CCRS COME IN ONE OF THREE POSSIBLE BREAKDOWN VOLTAGES: 45 V, 50 V, OR 120 V

Fourth & Fifth Characters	Breakdown Voltage	Example Part Numbers
“45”	45 V	NSI45020T1G, NSI45060JDT4G
“50”	50 V	NSI50010YT1G, NSI50350AST3G
“C2”	120 V	NSIC2020JBT3G, NSIC2050JBT3G

Problem Discussion

As seen in Figure 2 below, we have a bridge rectifier, CCR, and LEDs driven directly from the mains (equipment such as a fuse and metal−oxide varistor not used for this visualization). This schematic is based on the circuit from DN05013/D.

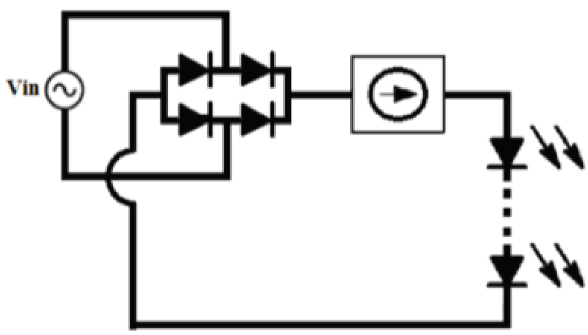

Figure 2. Schematic of a “Straight Circuit” Containing a Bridge Rectifier, CCRs, and Series LEDs.

According to the maximum conditions of the 220 Vac, and assuming a maximum +10% tolerance (meaning the voltage can reach 242 V_{AC} in extreme cases), we can have an overvoltage condition when using less than 222 V of LEDs, as described by Equation 1.

$$V_{bridge,max} = V_{RMS,max} * \sqrt{2} < V_{LED} + V_{AK,bkdn} \quad \text{(eq. 1)}$$

$$V_{bridge,max} = 242 * \sqrt{2} = 342\text{ V} < V_{LED} + 120\text{ V}$$

$$V_{LED} > V_{bridge,max} - V_{AK,bkdn} = 342\text{ V} - 120\text{ V}$$

$$V_{LED} > 222\text{ V}$$

When an LED load of less than 222 V is used, the overvoltage condition on the CCR would cause a current surge (CCR would stop regulating), and if used, the circuit fuse may blow. While a blown fuse prevents fires and other catastrophic circuit damage, even within normal mains voltage tolerances, the end−result is still a non−functional light bulb.

To correct this, an element is needed to “soak up” some of the voltage that would cause the CCR to breakdown. Due to the DC−like nature of LEDs, the load voltage cannot be increased, so another element must be inserted in series to take voltage off of the CCR, similar to the concept of Figure 1.

If at any point during operation the LED driver may be placed in an over−voltage scenario (due to transients, low LED load voltage, etc.), then the use of one of the protection techniques described in this note is highly recommended.

Solution Schematic and Operation

The modified circuits shown in Figure 3 demonstrate alternate implementations of active over−voltage protection for the CCRs. The N−type MOSFET M1, and power BJT Q2, act as on/off current paths for the CCR in conjunction with power resistor R4−the operational difference being the resistor drops a large DC voltage to conduct, whereas the transistors drop very little. The circuitry is activated by a high−voltage detector to conduct through the transistors at low−V_{AK} scenarios, and utilize the resistor to drop voltage at higher V_{AK} scenarios. Using this active trigger technique, the forward voltage of the current regulating block (CCR + OVP) can be nearly doubled from the CCR’s original 120 V_{AK} breakdown condition.

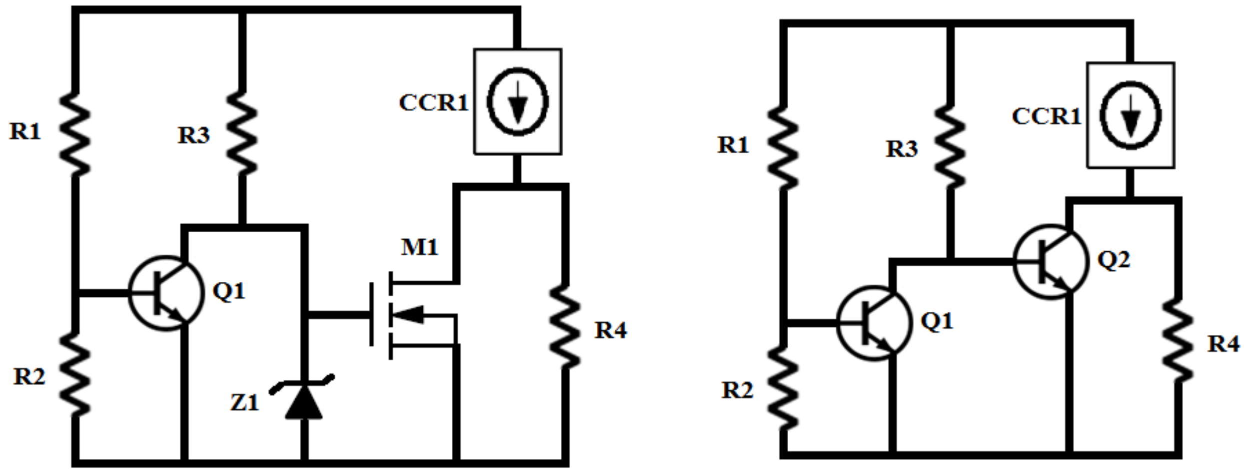

Figure 3. Two Functionally Equivalent Over−Voltage Protection Schemes. MOSFET−Based (left) Solution is Sightly More Efficient, while BJT−based (right) Solution has Lower Cost and Part Count

The R1/R2/Q1 system measures the voltage across the CCR and activates the over−voltage protection. When the voltage is high enough (according to Equation 2), based on the resistor divider, Q1's base−emitter junction turns on, causing the V_{CE} of Q1 to drop very low. This functional group is discussed in more detail in the "Active Trigger" section.

The MOSFET−based solution (Figure 3, left) uses an N−type MOSFET (M1) shunt a power resistor (R4) in certain high−voltage scenarios to keep the current−regulating device (CCR1) below voltage breakdown conditions. Selection of the MOSFET and relevant parameters are discussed later on in in the "MOSFET Selection and Design" section.

The BJT−based solution (Figure 3, right) operates similarly, using a power−type NPN transistor (Q2) to shunt a power resistor (R4) to keep the current regulator (CCR1) within appropriate voltage levels. The BJT−based option requires more careful design and is discussed in further detail in the "BJT Selection and Design" section.

It should be noted that the circuit blocks shown in Figure 3 are universally applicable at any mains voltage (i.e. 120 V_{AC}, 230 V_{AC}, etc.). The circuit in Figure 3 is a protection block across the CCR, and its voltage ratings are independent of the mains voltage. See Figure 4 for two possible configurations−note the topology remains largely similar between low and high−side implementations.

At lower voltages, the CCR may not be in danger of overvoltage breakdown as much as thermally−related reliability and lifetime issues. These techniques can be adapted to the same effect to reduce power dissipation on the CCR and remove heat, and increase the lifetime of the CCR.

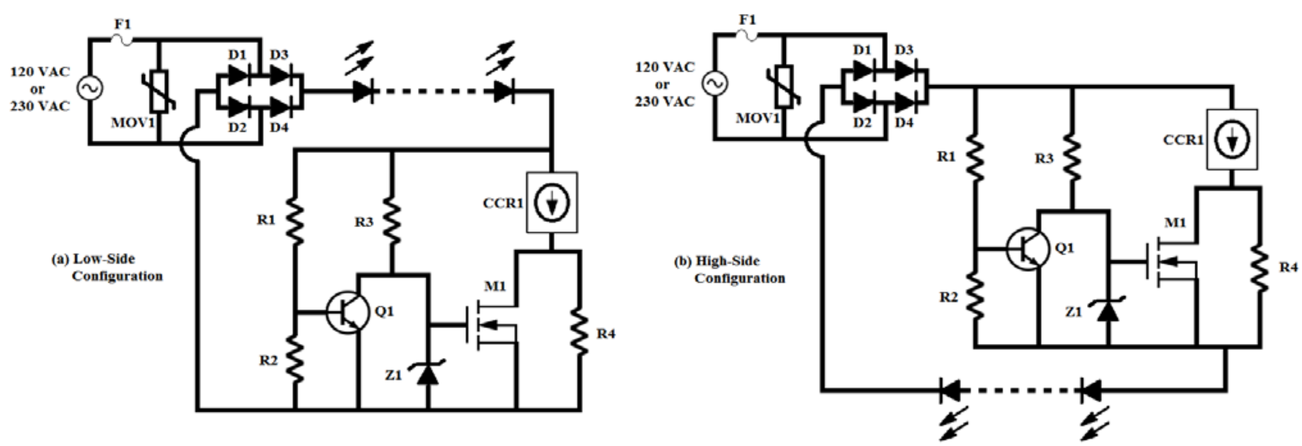

Figure 4. Low−Side (left) and High−Side (right) Driver Configurations with MOSFET−Based High−Voltage Protection Block

Active Trigger

The resistor divider R1/R2 divides the voltage between the anode of the CCR and the source of the MOSFET M1 (and emitter of Q1) and places it on the base−emitter junction of Q1, so this acts as a high voltage threshold detector. Since the distribution of $V_{BE,on}$ values for BJTs are generally very tight, the combination of R1, R2, and Q1 makes for a very effective high−voltage threshold detector, useful in other applications as well.

For extra precision, it is recommended that R1 and R2 be ±1% resistors. The switching point is determined by Equation 2, which as previously discussed, is loosely derived from the voltage rating on the CCR, minus some protection buffer.

$$V_{SWITCH(Q1)} = V_{BE,sat} * \frac{R1 + R2}{R2} \qquad \text{(eq. 2)}$$

A typical $V_{BE,sat}$ value for a transistor used here (such as an ON Semiconductor MMBT3904LT1G) at 25°C is about 0.68 V, for use in calculation.

Once on, Q1 draws current through R3, which should handily saturate the device, and a very low $V_{CE,Sat}$ will be achieved−far below the threshold of M1, or $V_{BE(ON)}$ of Q2. Empirical testing shows that a R1/R3 ratio of 10:1 (such as 1 MΩ for R1, and 100 kΩ for R3) yields satisfactory Q1 operation whether on 120 V or 230 V mains.

MOSFET Selection and Design

When using the MOSFET−based solution (Figure 3, left), as soon as the $V_{CE,Sat}$ of Q1 drops below the V_{TH} of M1, the drain−source channel shuts off and current is instead sent through the power resistor, R4. The resistor drops a voltage according to Equation 3, which is subtracted from CCR1's V_{AK}.

When selecting a MOSFET, care must be taken that the V_{drop} forced over the resistor does not exceed the V_{DS} voltage breakdown of the MOSFET. In most cases, a mid−voltage MOSFET with a breakdown around 100 V will suffice, such as the BVSS123LT1G. The V_{drop} forced over the resistor is shown by Equation 3 below. This V_{drop} is the DC voltage that is subtracted off of CCR1's V_{AK}.

$$V_{drop} = I_{CCR} * R_4 \qquad \text{(eq. 3)}$$

It is also good practice to include a voltage−regulating Zener diode (Z1) on the gate of a MOSFET for protection and increased reliability, as shown in Figures 3 and 5, especially when running with supply voltages higher than the maximum V_{GS} rating of the MOSFET. M1 turns on through the R3 resistor charging the gate capacitance, and then the gate voltage is regulated by Z1, which should be well above the MOSFET's threshold voltage.

The design of R3 is a careful balance between low power dissipation and circuit speed−the RC network created by R3 and the combined C_{GS} and Zener diode capacitance limits the response time of the circuit, however a higher R3 value increases circuit efficiency. Empirical testing yields that 100 kΩ is a balanced value for R3 when used with the BVSS123LT1G MOSFET and MMSZ5258BT1G Zener diode. However, it is generally possible to draw lower power using a MOSFET−based solution.

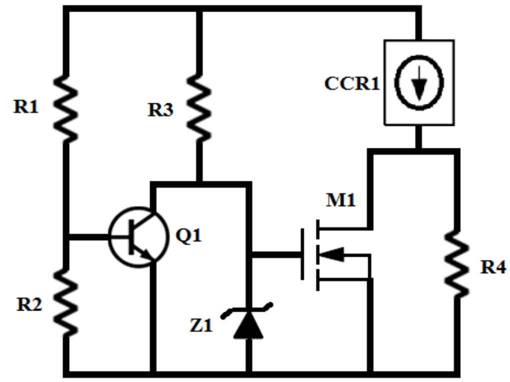

Figure 5. Schematic of a High−Voltage Protection Block Utilizing a MOSFET and Zener Diode

If the block as a whole enters reverse−bias, there is a path of two series diodes heading back to the supply (through M1 and CCR1), but this may be protected by using a bridge rectifier at AC, or reverse−protection diode at DC. BJT−based solutions without zeners and fewer parts exist as well, which will be reviewed in the "BJT Selection and Design" section.

Unlike the BJT−based option, the MOSFET−based OVP should only be implemented with N−channel/NPN devices. P−channel options would be considered impractical, but may be considered if the low $R_{DS,on}$ of a MOSFET is critical along with the different polarity. A sample bill of materials is included in the "Example Bill of Materials" section.

BJT Selection and Design

If it is undesirable to have both a MOSFET and Zener component, the BJT−based solution reduces total part count by one, as seen in Figures 3, 6 and 7. Simply replace the Z1 and M1 device with a single BJT, such as an NSS1C201LT1G or other NPN transistor with a similar voltage breakdown. Low $V_{CE,Sat}$ transistors, such as the NSS1C201LT1G, are recommended to give the circuit better efficiency and scalability across a range of LED currents. A sample bill of materials for an NPN−based solution is included in the "Example Bill of Materials" section.

The BJT−based solution employs the same principles as the MOSFET−based solution. According to R1/R2, Q1 turns on at a high voltage, which brings the V_{CE} of Q1 very low. When $V_{CE,Sat}$ of Q1 drops below 0.7 V, the base−emitter of Q2 is turned off, and current passes through the power resistor R4. Again, this resistor drops voltage according to Equatoin 3, which is subtracted from CCR1's V_{AK}.

However, R3's resistance and power rating must be carefully selected in order for Q2 to saturate while conducting CCR1's current. As a result, this topology is more difficult to scale across power levels or voltage range. Proper saturation of Q2 is important to decrease its own power dissipation and keep the device running properly, and increase circuit reliability. This is another reason low $V_{CE,Sat}$ devices can be advantageous (over general−purpose NPN transistors) for Q2.

Because the base current of Q2 is dependent on R3 and the supply voltage (according to Equation 4), and the saturation of Q2 is critical to proper operation, the schematic shown in Figure 6 is also well−suited to DC applications where the voltage is not expected to vary drastically. However it can also be made fit for a variety of AC scenarios when R3 is designed correctly.

$$I_{B,RMS} = \frac{V_{RMS}}{R_3} \qquad \text{(eq. 4)}$$

Equation 5 may be useful in obtaining a general value for R3, when RMS voltage on the CCR may be estimated. The β−parameter (also known as h_{FE}) is the operating gain of the BJT, which may be selected from a datasheet as a function of efficiency (higher β) and low $V_{CE,Sat}$ (lower β). For effective temperature−independent saturation, a β value of 10−30 is recommended.

$$R_3 = \frac{V_{RMS} \cdot \beta}{I_{CCR}} \qquad \text{(eq. 5)}$$

Similar to the MOSFET−based schematic, the Q2 transistor must possess a V_{CE} voltage breakdown greater than the voltage dropped on the resistor. In this case as well, Equation 3 also governs the voltage drop on the R4 resistor in the same way.

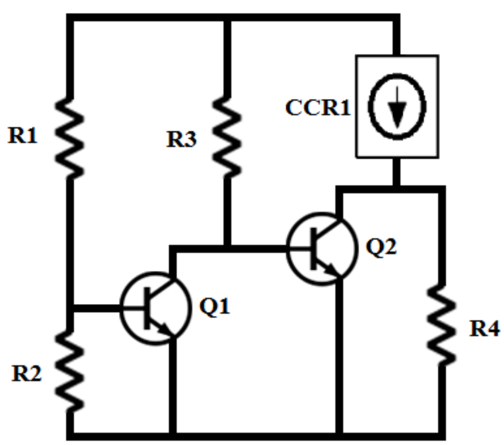

Figure 6. Schematic of a High−Voltage Protection Block Using only BJTs and Resistors

While considering BJT−based solutions, another available option is to flip the polarity and use PNP transistors to implement the OVP operation, as shown in Figure 7. Device designators were maintained in Figure 7 to ensure consistency of equations and most BOM values. Recommended transistors for Q1 and Q2 respectively are the MMBT3906LT1G and MMBT5401LT1G (see "Example Bill of Materials" section for other components).

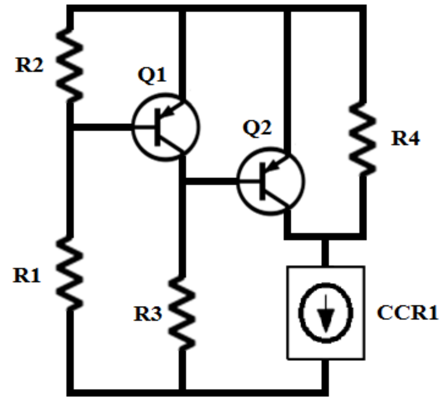

Figure 7. PNP−Based Schematic of a High−Voltage Protection Block

Practical Limitations

The CCR's 120 V_{AK} breakdown point also places a practical limitation on R4's V_{drop} value. To discuss these we will refer to the MOSFET−based schematic of Figure 5.

While M1 is on, R4 is shorted, and the current regulating block's voltage is primarily dropped on CCR1 (M1's V_{DS} channel drop is negligible). When M1 is turned off, R4 becomes the series element with the CCR, and before the supply voltage has a chance to rise, the voltages follow the transition outlined in Equation 6.

$$V_{AK,before} \rightarrow V_{AK,after} + V_{drop} \qquad \text{(eq. 6)}$$

Let us say the term $V_{AK,before}$ is limited to 110 V (10 V below breakdown levels is effective guardband). For the CCR to remain in full regulation after the transition, about 10 V_{AK} is recommended for robust operation. This leaves the V_{drop} over R4 limited to 100 V maximum−a limit which is completely independent of supply voltage−as calculated by Equation 3 again. As a result, when using 120 V_{AK} breakdown devices, an appropriate V_{drop} value for the R4 resistor may be anywhere between 50 V and 100 V. Recalling Figure 1 again, this yields a total current−regulating block breakdown voltage of up to 220 V. For 45 and 50 V parts, after buffering for both guardband and continual−operation V_{AK} voltages, suggested V_{drop} values could be between 15 V and 30 V.

If higher voltage breakdowns are desired, this block can be stacked, and multiple stages can be used in succession or at multiple points in a circuit with negligible efficiency losses.

Other Solutions

Other topological techniques to protect CCRs from overvoltage conditions include using a capacitive−drop topology (as reviewed in the application note AND8492/D), or even careful balancing of the LED load voltage (such as the design note DN05047/D). Although these techniques have proven to be effective in safely protecting CCRs, these solutions possess application specifics that make them not as widely applicable as the solutions presented in detail in this technical note.

Inserting a resistor in series with the LEDs will also reduce V_{AK} from the CCR, dropping a fixed voltage (see Equation 3) after the LEDs turn on. However, this occurs at the expense of increasing the turn−on voltage of the LEDs, which reduces light output from the LEDs and reduces driver efficiency. This solution should only be employed when the number of LEDs (or LED voltage) cannot be increased any further, but the extra voltage guardband is desired. Additionally, a simple resistor in series will not effectively guard against supply voltage tolerances−active protection schemes (Figure 3) maintain light output levels much better while protecting devices across voltage range.

Another inferior, but functional overvoltage protection solution would be to place CCRs in series with parallel zeners, as seen in Figure 8. This solution increases cost, yet optimizes for the smallest footprint and part count. Power dissipation tends to be uneven on the CCRs due to regulation current tolerance differences, reducing overall system lifetime. Each Zener diode must have a voltage regulation rating less than the breakdown of the CCRs, and the total voltage drop must not exceed the sum of the Zener voltages.

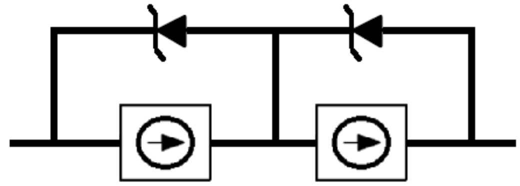

Figure 8. CCRs May Be Deployed in Series with Parallel Zener Diodes as a Costly, but Space−optimized, OVP Scheme

Example Bill of Materials

Table 2 below presents a sample bill of materials that could be used to add an additional 80 V to the V_{AK} of the current regulating block (i.e. V_{drop} from Equation 3 equals 80 V) when using an NSIC2050JBT3G, a 50 mA, 120 V CCR. Table 3 offers a sample bill of materials for the BJT−based design, recommending a low $V_{CE,sat}$ NPN transistor to reduce part count and ensure high efficiency.

Table 2. SAMPLE BILL OF MATERIALS FOR THE MOSFET/ZENER−BASED HV PROTECTION CIRCUIT

Designator	Manufacturer	Part No.	Qty	Description	Value	Tol.
CCR1	ON Semiconductor	NSIC2050JBT3G	1	Constant Current Regulator	120 V, 20 mA	±15%
M1	ON Semiconductor	BVSS123LT1G	1	N−Channel MOSFET	100 V, 170 mA	−
Q1	ON Semiconductor	MMBT3904LT1G	1	NPN Transistor	40 V, 100 mA	−
R1	Any	−	1	Resistor	1 MΩ, 0.125 W	±1%
R2	Any	−	1	Resistor	6.8 kΩ, 0.125 W	±1%
R3	Any	−	1	Resistor	100 kΩ, 0.125 W	−
R4	Any	−	1	Resistor	1.6 kΩ, 0.5 W	−
Z1	ON Semiconductor	MMSZ5258BT1G	1	Zener Diode	15 Vz	±10%

Table 3. SAMPLE BILL OF MATERIALS FOR THE NPN BJT−BASED HV PROTECTION CIRCUIT

Designator	Manufacturer	Part No.	Qty	Description	Value	Tol.
CCR1	ON Semiconductor	NSIC2050JBT3G	1	Constant Current Regulator	120 V, 20 mA	± 15%
Q1	ON Semiconductor	MMBT3904LT1G	1	NPN Transistor	40 V, 100 mA	−
Q2	ON Semiconductor	NSS1C201LT1G	1	Low $V_{CE,sat}$ NPN Transistor	100 V, 2 A	−
R1	Any	−	1	Resistor	1 MΩ, 0.125 W	± 1 %
R2	Any	−	1	Resistor	6.8 kΩ, 0.125 W	± 1 %
R3	Any	−	1	Resistor	82 kΩ, 0.125 W	−
R4	Any	−	1	Resistor	1.6 kΩ, 0.5 W	−

Conclusion

Constant Current Regulators are a simple and versatile linear LED driver that can be used in a wide variety of direct−AC applications. Simple circuitry can be implemented to protect the driver from high voltage conditions, effectively increasing the voltage drop over a linear LED driver in a direct AC application.

The techniques described in this application note can be used to “extend” the current regulator’s voltage ratings, as well as decrease power dissipation and improve device reliability and lifetime. Multiple solution schematics were proposed and discussed in detail, with supporting equations and schematics.

With ON Semiconductor CCRs, there are numerous ways to actively protect and extend the operation of the CCR during normal operation, increasing their effectiveness and in−driver portability.

References

1. DN05013/D, “Simple ENERGY STAR® Compliant LED Driver Retrofit in a T5 Tube using 160 mA CCR,” Yohai Kalderon. ON Semiconductor. http://www.onsemi.com/pub_link/Collateral/DN05013−D.PDF
2. AND8492/D, “Capacitive Drop Drive Topology with a Constant Current Regulator to Drive LEDs,” ON Semiconductor. http://www.onsemi.com/pub_link/Collateral/AND8492−D.PDF
3. DN05047/D, “230 Vac, Low−Cost, Dimmable, Three−Stage, LED Lamp Circuit,” Andrew Niles. ON Semiconductor. http://www.onsemi.com/pub_link/Collateral/DN05047−D.PDF

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