AND8433/D

Using ON Semiconductor Constant Current Regulator (CCR) Devices in AC Applications

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APPLICATION NOTE

Introduction

This update includes additional information on 220 V ac lighting circuits with the addition of ON Semiconductors 120 V breakdown family of CCRs.

LEDs for AC and DC lighting pose a challenge to lighting designers. Technology for High Brightness (HB) LEDs is rapidly advancing. There are several existing solutions to drive these devices: Switching power devices (buck, boost, and buck-boost), linear regulators and resistor bias circuits. Each has its merits and drawbacks. One thing is common to all. LEDs need to be driven by a constant current source for maximum efficiency (lumens per watt), color and lifetime.

Switching regulator topology can be costly, cause EMI, and require additional circuit elements. Linear regulator circuits are less costly; but, may require additional components and are less efficient. Resistor bias is the least expensive method to set a current for a specific voltage. The drawback is that the current changes with a change in input voltage.

ON Semiconductor has developed a family of cost effective Constant Current Regulators (CCR) that will simplify circuit design while meeting the consensus requirement to keep the LED under a constant current condition.

The CCR can be represented as a variable resistor. As the voltage increases across the device, the internal resistance of the CCR increases to maintain a current close to the specification (I_{reg}). The CCR also has a negative temperature coefficient, thus as power is dissipated by the CCR (increased temperature), its internal resistance increases causing a reduction in current. The CCR has a higher regulating current when pulsed compared to that at a steady state DC current because the die has not reached thermal stability.

The rectified AC waveform is similar to a pulsed signal. The regulating current will change as the power dissipation changes.

The purpose of this paper is to explore the utilization in AC lighting applications with 110 V, and 220 V AC rms input for CCR devices Figure 1.

An AC output from a Full Wave Bridge rectifier produces a varying dc voltage which has a value with time of: Vi = Vpk sin(2πft). The value for 2πf is 377 for a 60 Hz waveform and 314 for a 50 Hz waveform.

As the voltage is rising across the series configuration of CCR device and LED string it will reach the forward voltage of the LED string (Vf x Number of LEDs). At this point, the LED string voltage will begin to remain constant. About 1.8 V beyond this LED turn on point, the CCR will turn on to maintain a constant current through the LEDs. The voltage across the CCR will be the difference between the total LED Vf and the Vi up to Vpk. This process reverses on the falling side of the rectified voltage. The effect is to have a PWM (Pulse Width Modulation) of the LEDs at 120 Hz for a 60 Hz waveform or 100 Hz for a 50 Hz waveform. Using a 30 mA steady state CCR in a 120 V AC application results in 22 mA rms due to pulsed operation from full wave bridge rectification. This paper describes applications from new to retrofit circuit designs. The operating range of the CCR in AC circuits is from 1.8 V to 120 V. See appendix B for terms used in AC analysis.

The LED on time will depend on the forward voltage drop of the LED string. In the circuits referenced in this application, the CCR on time is about half the peak voltage on time. Thus the LEDs are on for about 50% of the time. The rms current through the LEDs is therefore about 50% of the regulating current.

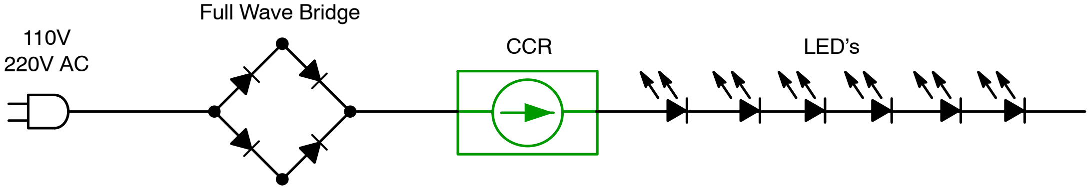


Figure 1. Basic AC Application

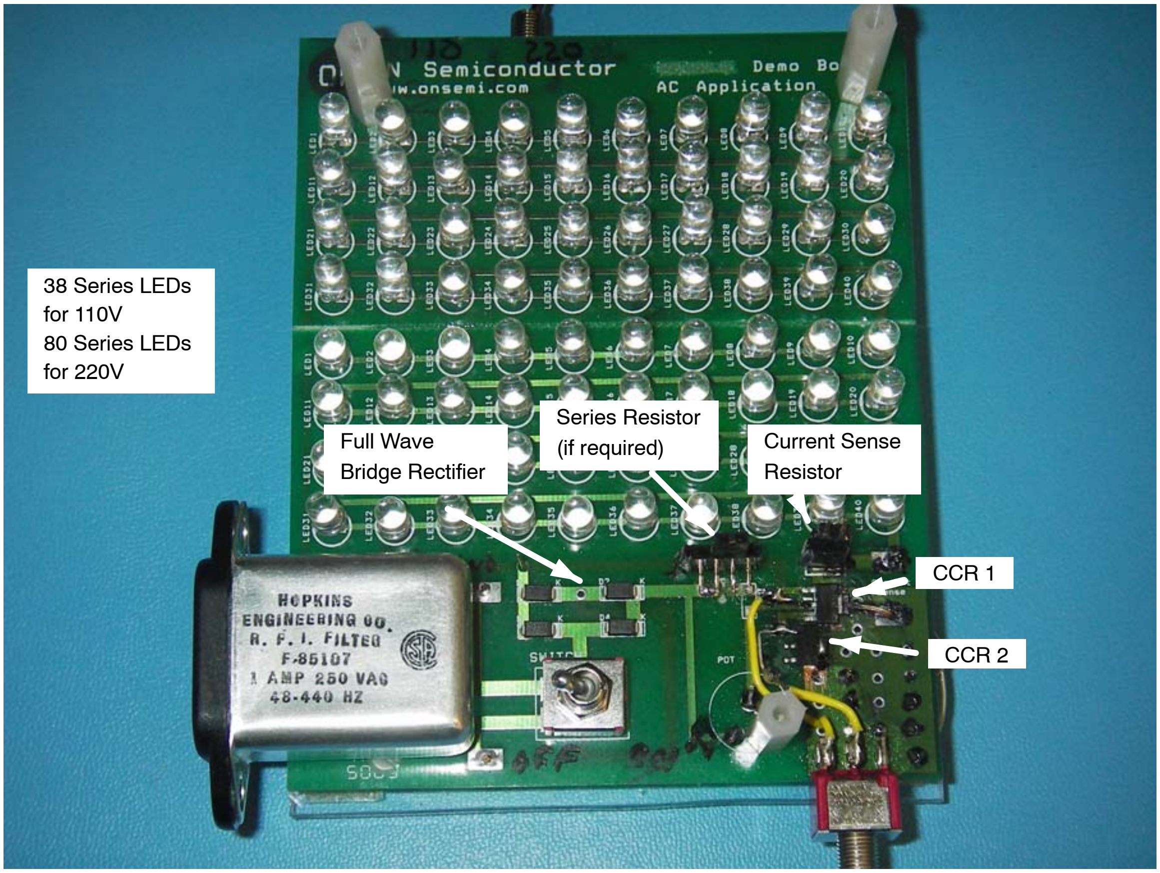


Figure 2. Demonstration PCB used for 110 V & 220 V AC rms analysis

DESIGN EXAMPLE 1: New Design with a CCR

This design selects the number of series LEDs.
Design parameters: 110 VAC rms, +/- 10%, HB LEDs (V_F of 3.3 V at 20 mA).
Analysis for Vin = +10% (max)
To calculate the number of LEDs for Vin Maximum = (110 V rms + 10%) = 120 V rms
Rectified Vpeak = 120 V rms x 1.414 = 170 V
V_F of LED string = 170 V (peak Vin) – 45 V (Vak max) = 125 V (V_F led string)
# of LEDs = 125 V / 3.3 V = 38 LEDs

Analysis for Vin = -10% (min)
Testing for minimum Vin: (110 Vrms – 10%) = 100 Vrms
Rectified Vpeak = 100 Vrms x 1.414 = 141 V (peak Vin)
CCR Vak is: 141 V (peak Vin) – 125 V (V_F LED string) = 16 V
The Vak range will vary with the number of LEDs in the string. Adding 3 additional LEDs will set the Vak range from 6 V to 35 V. The additional HB LEDs provides greater luminosity and reduces CCR thermals.

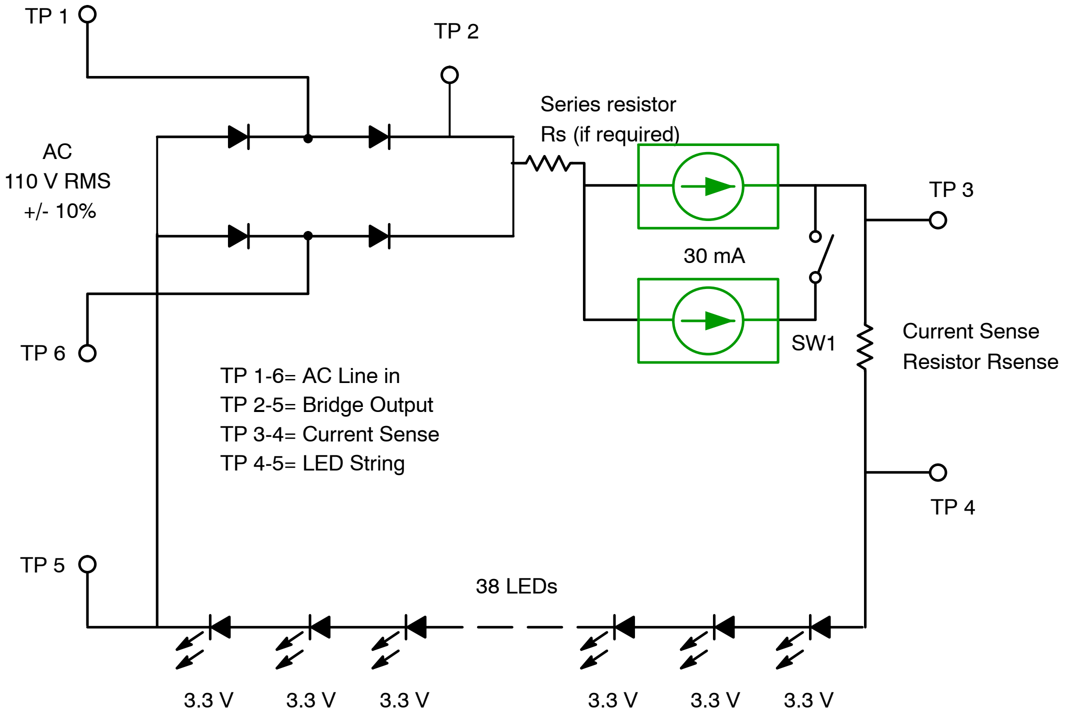


Figure 3. Direct AC Line LED Circuit with CCR

The AC rms voltage is full wave rectified into pulsating DC at a frequency of 120 Hz. The CCR turns on when the voltage exceeds the V_F for the LEDs and the bridge rectifier, controlling the current and isolating the LEDs from the peak rectified voltage.

Thermal Analysis of Design Example 1

(120 VAC, 38 LEDs)
The power dissipation of the CCR for Figure 3 is determined by:
(Vak rms) x (I_{REG} * Duty Cycle)
Vak rms = Vbridge rms - LED string $V_{F\ rms}$
(120 Vbr rms-(38 x 3.3 V LED x 0.707) x (30 mA x 50%)
= 31 V rms x 15 mA = 465 mW

A SOT-223 with a 100 mm^2 1 oz Cu heat spreader will operate up to 85°C.

The data sheet power dissipation tables show various combinations for other ambient temperatures.

The following oscilloscope traces (Figures 4, 5 and 6) are for a 110 V ±10% AC rms input with 38 LEDs in series. The regulated current is measured by using a 100 Ω, 1% sense resistor. The measurements show the rms voltage across the sense resistor with the rms current below the voltage measurement. The circuit is similar to Figure 3 using a single NSI45030AZT1G 30 mA CCR. The heatsink for the CCR on this test PCB is 500 mm^2.

All waveforms were taken using differential voltage probes.

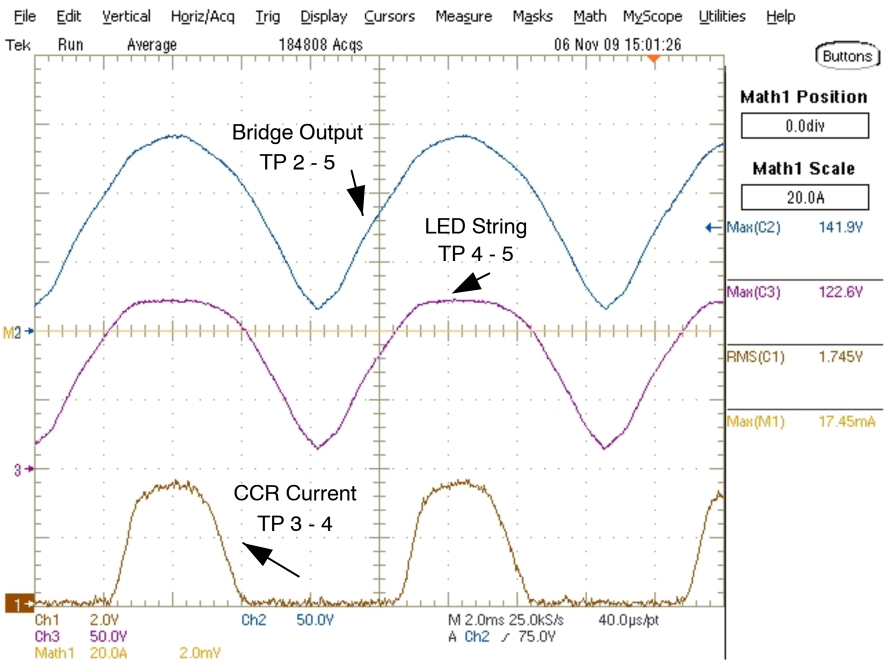


Figure 4. 100 V rms 1 x 30 mA CCR Analysis

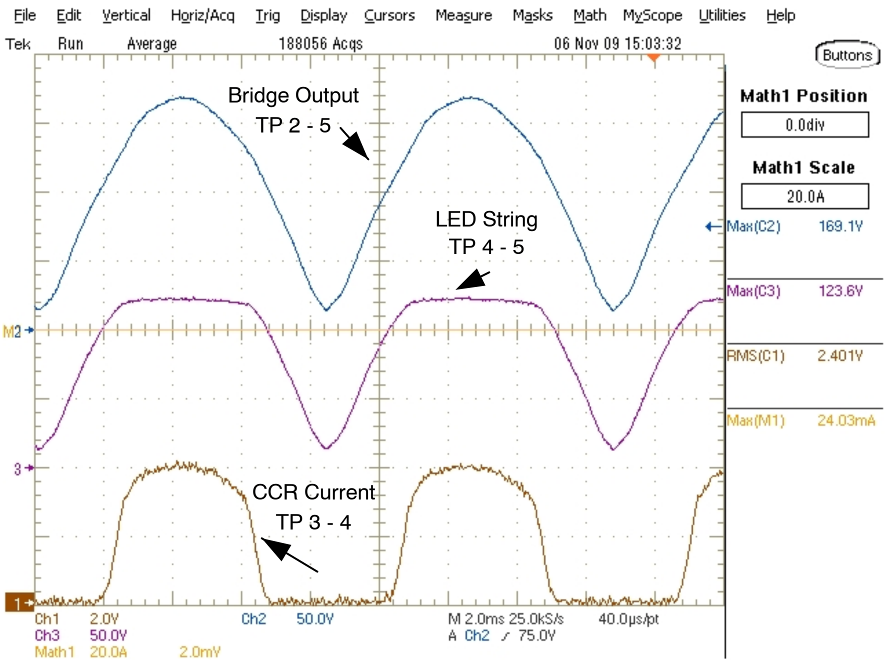


Figure 5. 120 V rms, 1 x 30 mA CCR Analysis

CCRs can be operated in parallel to increase the regulated current supplied to the circuit. The waveforms of Figure 6 were taken with two 30 mA CCRs operated in parallel (Figure 3, SW 1 closed).

The LED intensity is increased when the supplied current is doubled. The LED V_F increases by less than 10% with a 100% increase in drive current.

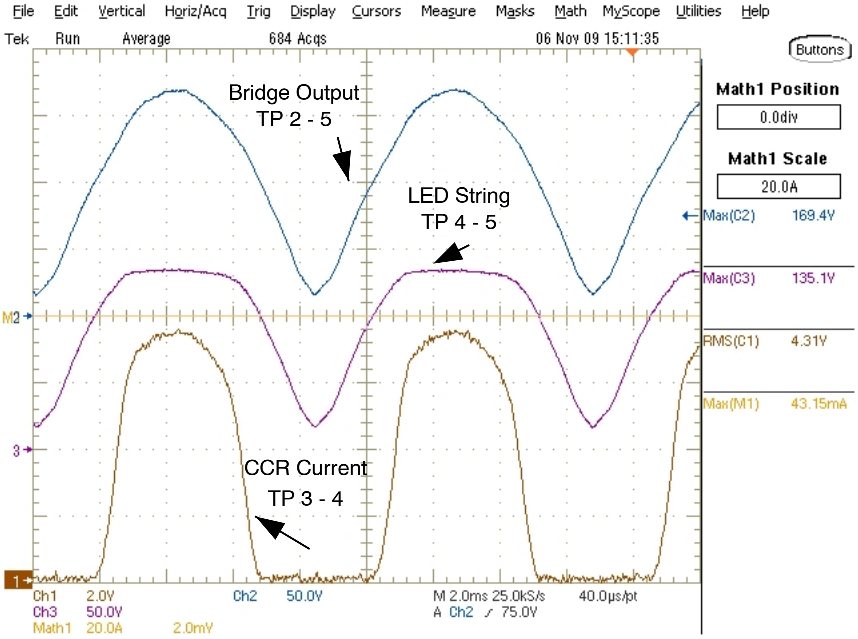


Figure 6. 120 V rms, 2 x 30 mA CCR Analysis

In summary for 110 VAC operation:

Table 1

Vin AC V rms	V rectified V Peak	CCRs	CCR Ireg mA rms	V_F LED String VPeak	Vak CCR VPeak
100	141	1 CCR	18	123	18
110	156	1 CCR	21	124	32
120	170	1 CCR	24	124	46
120	170	2 CCRs	43	135	34

220 V AC ANALYSIS

All that is required to use a CCR at 220 V AC rms are additional LEDs.

The following oscilloscope traces were taken on a similar circuit to Figure 3 operating at 220 V AC rms with 80 LEDs in series:

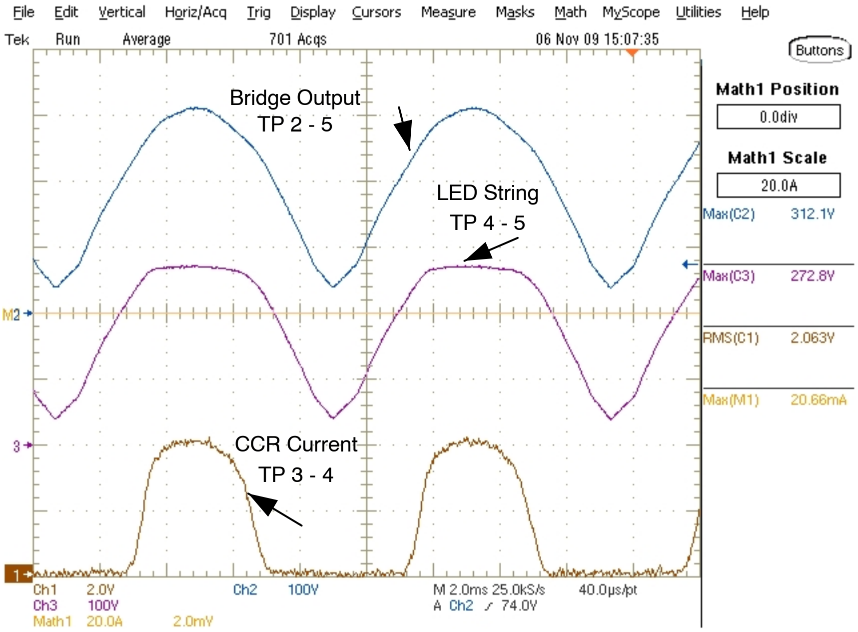


Figure 7. 220 V rms, 1 x 30 mA CCR Analysis

The following oscilloscope traces were taken on a similar circuit to Figure 3 operating at 220 V AC rms ± 10% with 68 LEDs in series using a 120 V, 50 mA CCR device:

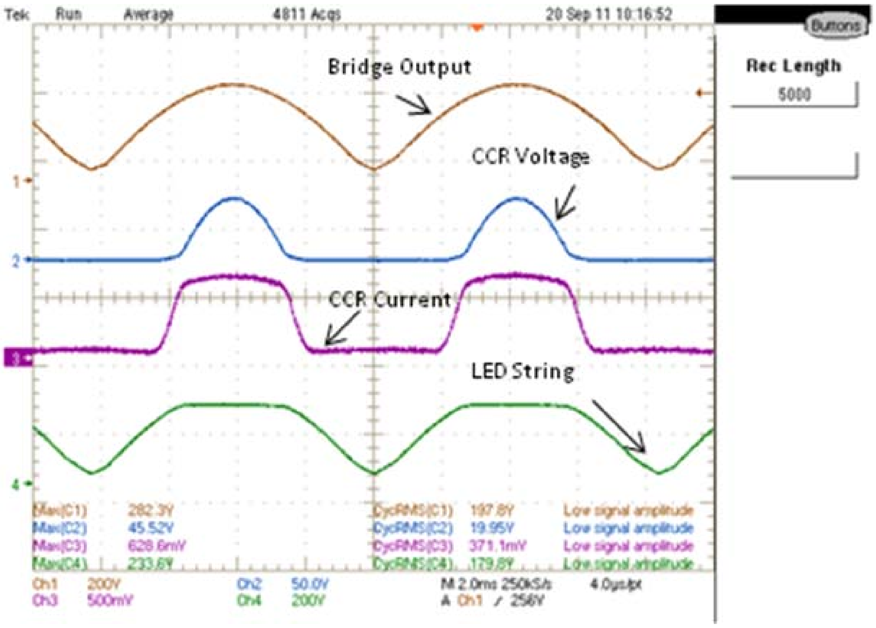
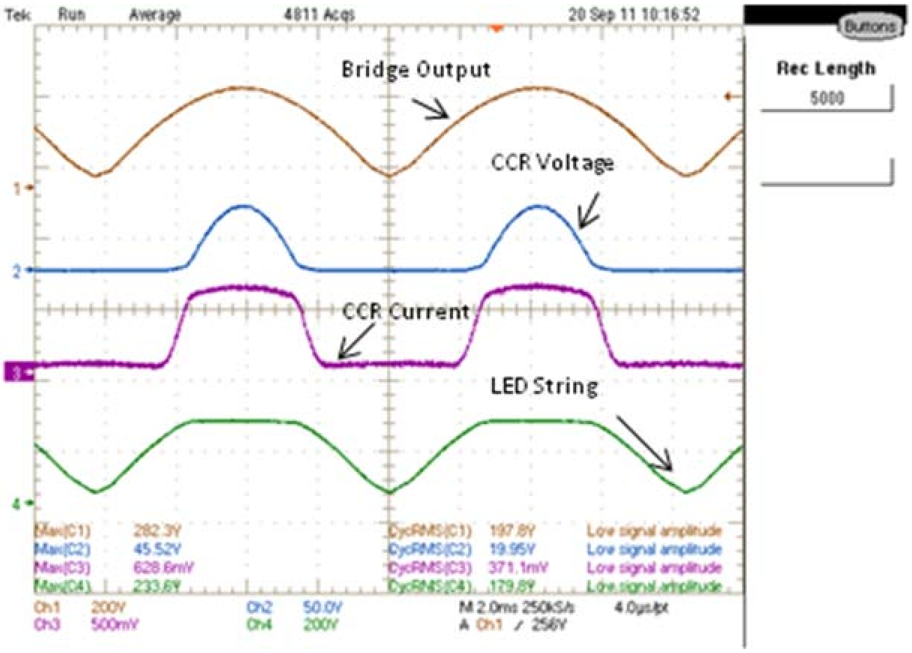


Figure 8. 198 V rms, 1 x 50 mA CCR Analysis



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Max(C1)    282.3V     CycRMS(C1)  197.8V    Low signal amplitude
Max(C2)    45.52V     CycRMS(C2)  19.95V    Low signal amplitude
Max(C3)    628.6mV    CycRMS(C3)  371.1mV   Low signal amplitude
Max(C4)    233.6V     CycRMS(C4)  179.8V    Low signal amplitude
Ch1   200V        Ch2   50.0V     M 2.0ms 250kS/s   4.0μs/pt
Ch3   500mV       Ch4   200V      A Ch1  ∕  256V
```

Figure 9. 242 V rms, 1 x 50 mA CCR Analysis

Thermal Analysis of Design Example Figure 9
(242 VAC, 68 LEDs)
The power dissipation of the CCR for Figure 3 is determined by:
(Vak rms) x ($I_{REG\ RMS}$)
Vak rms = 57.7 V , Irms = 38 mA (from screenshot Figure 9)
57.7 V x 38 mA = 2.19 W

This CCR is mounted on a 1000 mm^2, 3 oz Cu, FR4 heat spreader will operate up to T_A of 50°C for a T_J of 175°C. Adding additional LEDs will reduce the power dissipation of the CCR and allow for a higher T_A operation. The data sheet power dissipation tables show various combinations for other ambient temperatures. All waveforms were taken using differential voltage probes.

DESIGN EXAMPLE 2: Retrofitting using a CCR (Figure 10)

Design parameters: 110 V AC rms, +/- 10%, existing design using 24 LEDs (V_F of 3.3 V at 22 mA)

A series dropping resistor (Rs) will be chosen to keep the CCR within its operating limits.

Rectified Vpeak (maximum) = 120 V rms x 1.414 = 170 V

V_F of LED string = 24 x 3.3 V = 79.2 V

The voltage drop required is: Vpeak – (V_F leds pk + Vak CCR pk +VRsense pk)

V drop of Rs = 170 V – (79.2 V + 45 V + 4) = 41.8 V

CCR pk current is 34 mA; therefore, Rs = 41.8 V / .034 A = 1229 Ω (circuit tested with 1200 Ω RS)

The power dissipation is V x I = 1.42 W pk or 1.0 W RMS.

Testing for minimum Vin: 110 V rms x 0.9 = 100 V rms using a 1200 Ω Rs

Rectified Vpeak = 100 Vrms x 1.414 = 141 V

CCR Vak is 141 V – (79.2 + 41.8 +4) = 16 V

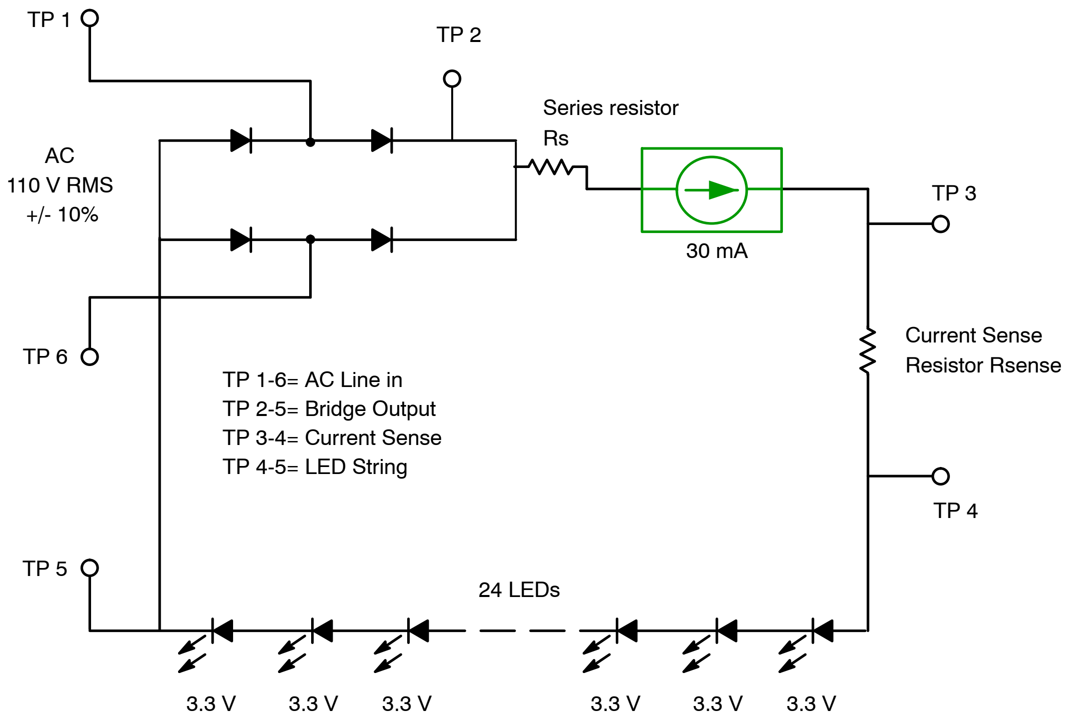

Figure 10. Direct AC Line LED Circuit with CCR

24 LEDS, 1200Ω Rs, 1 CCR, 100 Ω Rsense, 25°C

TDS5104B Oscilloscope Measurements	Max	rms		Max	rms
Bridge output	141	98	VLEDs	80	64
VRs+Vak+VRsense	61	34	VRsense	3.6	2.1
VRs+Vak	57.4	31.9	Vak	15.6	6.5
VRs	41.8	25.4	VRs	41.8	25.4
Bridge output	155	107	VLEDs	80.8	65
VRs+Vak+VRsense	74.2	42	VRsense	3.9	2.4
VRs+Vak	70.3	39.6	Vak	26.3	11.6
VRs	44	28	VRs	44	28
Bridge output	171	117	VLEDs	81.7	65.6
VRs+Vak+VRsense	89.3	51.4	VRsense	3.9	2.8
VRs+Vak	85.4	48.6	Vak	39	18
VRs	46.4	30.6	VRs	46.4	30.6

Actual 24 LED, 1200Ω series resistor circuit measurements

Power Dissipation for 120V AC rms	Max	rms
Ireg A	0.039	0.028
P_D Rs (W)		0.8568
P_D CCR (W)		0.504
P_D Rsense (W)		0.0784
P_D LEDs (W)		1.8368
Total P_D (W)		3.276

Summary

The CCR can be represented as a variable resistor. As the voltage increases across the device the internal resistance of the CCR increases to maintain a current close to the specification (I_{reg}). The CCR also has a negative temperature coefficient, thus as power is dissipated by the CCR (increased temperature) the internal resistance is increased causing a reduction in current. This prevents thermal runaway and protects the LEDs increasing their life and reliability. The CCR has a higher regulating current when pulsed compared to that at a steady state DC current because the die has not reached thermal stability.

The rectified AC waveform is similar to a pulsed signal, the regulating current will change as the power dissipation changes.

The LED on time will depend on the forward voltage of the LED string. In the circuits referenced in this application it is about half the peak voltage and thus the LEDs are on for about 50% of the time. The rms current through the LEDs is therefore about 50% of the regulating current.

See Appendix C for Application Notes, Design Notes and Technical Demonstration list.

Appendix A:

SOD-123 devices are:
NSI45015WT1G, Steady State I_{REG} = 15 mA±20%
NSI45020T1G, Steady State I_{REG} = 20 mA±15%
NSI45025T1G, Steady State I_{REG} = 25 mA±15%
NSI45030T1G, Steady State I_{REG} = 30 mA±15%
NSI45020AT1G, Steady State I_{REG} = 20 mA±10%
NSI45025AT1G, Steady State I_{REG} = 25 mA±10%
NSI45030AT1G, Steady State I_{REG} = 30 mA±10%
NSI50010YT1G, Steady State I_{REG} = 10 mA±30%

SOT-223 devices are:
NSI45025ZT1G, Steady State I_{REG} = 25 mA±15%
NSI45030ZT1G, Steady State I_{REG} = 30 mA±15%
NSI45025AZT1G, Steady State I_{REG} = 25 mA±10%
NSI45030AZT1G, Steady State I_{REG} = 30 mA±10
NSI45020JZT1G, Adjustable I_{REG} = 20−40 mA±15%
NSI45035JZT1G, Adjustable I_{REG} = 35−70 mA±15%

DPAK devices are:
NSI45060JDT4G, Adjustable I_{REG} = 60−100 mA±15%
NSI45090JDT4G, Adjustable I_{REG} = 90−160 mA±15%
NSI50350ADT4G, Steady State I_{REG} = 350 mA±10%

SMC devices are:
NSI50350AST1G, Steady State I_{REG} = 350 mA±10%

SMB devices are:
NSIC2050BT3G, Vak max = 120V, Steady State I_{REG} = 50 mA±15% (Product Preview)
NSIC2030BT3G, Vak max = 120V, Steady State I_{REG} = 30 mA±15% (Product Preview)
NSIC2020BT3G, Vak max = 120V, Steady State I_{REG} = 20 mA±15% (Product Preview)

SC-74 devices are:
NSI45019JPT1G, Adjustable I_{REG} = 19-35 mA±15%, PWM enhanced (Product Preview)

Appendix B:

For AC (Alternating Current) analysis of series LED circuits, we will be using the following terms:
Vin = The input AC Line voltage applied expressed as rms or Stepped down with a transformer.
Vpeak = Highest Vin with a sinusoidal voltage (Vin x 1.414)
Vbridge rms = Vpeak x 0.707
$V_{F\ rms}$ = V_F LED x 0.707
Rs = series dropping resistor if required.
Rsense = series resistor to measure current. V measured / 100 Ω, 1% resistor = current
Ireg = regulated circuit current
Ireg rms = Ireg peak x duty cycle (approximately 50%).
Reference to Data Sheet:
The data sheet describes the devices and defines the following terms that will be used throughout this note:
Vak = Voltage applied between the Anode and Cathode of the device.
P_D = Device power dissipation, typically in W.
T_A = Ambient Temperature in °C
T_J = Device Junction Temperature in °C

Appendix C:

AND8349/D Automotive Applications: The Use of Discrete Constant Current Regulators (CCR) For CHMSL Lighting
AND8492/D Capacitive Drop Drive Topology with Constant Current Regulator to Drive LEDs
AND8220/D How To Use Thermal Data Found in Data Sheets
AND9008/D Thermal Considerations for Discrete Constant Current Regulators in DPAK, SMC and SMB Packages for Driving LEDs
AND8391/D Thermal Considerations for the ON Semiconductor Family of Discrete Constant Regulators (CCR) for Driving LEDs in Automotive Applications
DN05013/D NSI45090JD: ENERGY STAR® Compliant LED Driver Retrofit in T5 Tube Using 160 mA Constant Current Regulator
DN05021/D High Efficiency - Low Cost LED Dimming
DN05022/D ENERGY STAR® Compliant - Low Cost LED Dimming
TND402/D Constant Current Regulator Driver for T8 Fluorescent Light
TND403/D Constant Current Regulator Solutions for Driving LEDs

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