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120 V_{AC}, Low-Cost, Dimmable, Linear, Parallel-to-Series with Switch-In CCR LED Lighting Circuit

DESIGN NOTE

Table 1. DEVICE DETAILS

Device	Application	Topology	Efficiency	Input Power	Power Factor	THD
NSIC2030JB, NSIC2050JB	AC LED Lighting	Linear	79%	7.9 W	0.99	12%

Overview

This circuit is an innovative take on the parallel-to-series topology and provides an effective 120 V_{AC} LED lighting solution. Its primary features are its PF and THD performance, dimmability, low cost, and high efficiency and light output.

This circuit uses a parallel-to-series topology that dynamically adjusts LED forward voltage as the bridge output varies. The circuit also switches two CCRs independently to match the input current waveform to the bridge output voltage for excellent PF and THD performance.

The circuit is designed for input voltages between 110 V_{AC} and 130 V_{AC}.

The circuit uses ON Semiconductor CCRs to provide constant LED current and protect LEDs from over-voltage conditions. The circuit also employs a second CCR to increase LED current at high voltages for improved PF and THD performance.

Key Circuit Features

- Functional with Standard Phase-Cut Dimmers
- Low-Cost
- PF > 0.99
- THD = 12%
- Adjustable for Different LED Voltages
- Adjustable for Different Power Levels/Currents

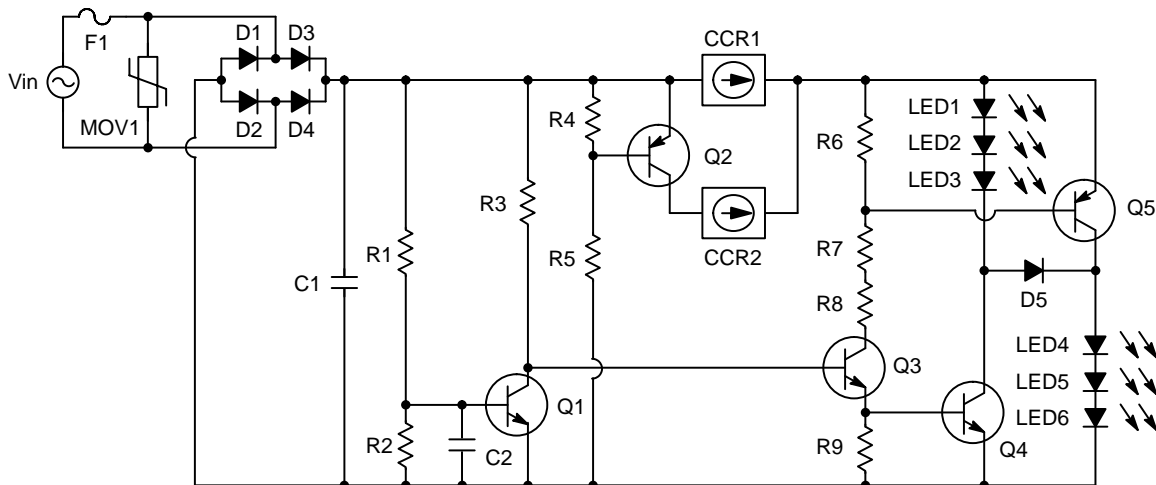


Figure 1. 2-stage Parallel-to-Series LED Lighting Circuit, with Switch-In CCR

Circuit Description

The circuit consists of a full-wave bridge rectifier (D1–D4), parallel-to-series switching circuitry (C1–C2, R1–R3, R6–R9, Q1, Q3–Q5, D5), CCR switching circuitry (C3, R4–R5, Q2), CCRs (CCR1–CCR2), and LEDs (LED1–LED6).

Circuit Operation

The full-wave bridge rectifier outputs a positive half-sine wave peaking at 170 V (120 V_{AC}). The rectified supply voltage is referenced between the cathodes of D3 and D4 and the anodes of D1 and D2.

The circuit has two different switching mechanisms acting at all times. The first is the parallel-to-series switching component, which controls the effective LED forward voltage (V_f) seen by the circuit. The parallel-to-series switching components are driven by the Q1 transistor, whose V_{BE} is driven by the R1/R2 voltage divider. With the chosen R1/R2 values in this circuit, this switching voltage is 122 V[†].

The second switching component in the circuit is the switch-in CCR, wherein a second CCR (CCR2) switches on at high voltages to provide additional input current, boosting PF and lowering THD. The transistor Q2 acts as a switch for CCR2. Q2's V_{BE} is driven by the R4/R5 voltage divider. By the chosen values in this circuit, this switching voltage is 116 V^{††}. With about 8 V across the CCR2 to ensure full regulation, this additional current activates at about 124 V bridge output.

At low voltages (bridge output < 122 V), the LEDs are in a parallel configuration for earlier turn-on, and CCR2 is off. Q1 is off, leaving Q3 on and supplying base current for Q4 and Q5, each providing a separate current path for the two strings of LEDs.

When the bridge output surpasses 122 V, the LEDs switch into series mode, effectively doubling the forward voltage of the LEDs and protecting the CCRs from over voltage in the circuit. CCR2 is still off at this point.

When the bridge output increases past 124 V, CCR2 begins to switch on, providing more current to the LEDs. It is important to ensure that CCR2 turns on after the LEDs enter into the series configuration to provide the most sinusoidal input current waveform possible. The late turn-on also improves efficiency.

[†]A typical value for the $V_{BE(sat)}$ of Q1, an ON Semiconductor MMBT3904L, at 25°C is 0.68 V. With the values R1 = 1 M Ω and R2 = 5.6 k Ω , the turn-on voltage for Q1 may be found using the following formula:

$$V_{SWITCH(Q1)} = V_{BE(sat)} \cdot \left(\frac{R1 + R2}{R2} \right)$$

Using these values, $V_{SWITCH(Q1)}$ is about 122 V.

^{††} Similarly, we may calculate the turn-on voltage of Q2, an ON Semiconductor MMBT5401L. A typical $V_{BE(sat)}$ for

this device at 25°C is 0.68 V. Using the values R4 = 590 Ω and R5 = 100 k Ω in the formula:

$$V_{SWITCH(Q2)} = V_{BE(sat)} \cdot \left(\frac{R4 + R5}{R4} \right)$$

Using these values, $V_{SWITCH(Q2)}$ is about 116 V.

Design Considerations

In the modification of this circuit, it is important to consider several specifics in its design.

The driver is tunable to drive between 60 to 160 V of LEDs in two strings (30–80 V per string). To protect CCRs from over-voltage conditions the total V_f of all LEDs in the series stage should be greater than 60 V. To obtain the benefit of the parallel configuration stage, the total LED V_f of one string should be less than 80 V. (Example 1: Two strings of 16 LEDs with $V_f = 3.2$ V, one string $V_f = 51.2$ V, total series $V_f = 102.4$ V. Example 2: Two strings of 3 LEDs with $V_f = 20$ V, one string $V_f = 60.0$ V, total series $V_f = 120.0$ V)

The use of higher V_f LED strings will boost circuit efficiency, but with a later LED turn-on voltage, will reduce dimmability and PF/THD.

If greater currents are desired through CCR2 and Q2, a darlington-connected PNP pair (may use two MMBT5401L devices) or a PFET may be considered to reduce base current and obtain higher gain. Multiple CCRs may be added in parallel to CCR1 at no consequence to the circuit.

Circuit Performance Data

Table 2. PERFORMANCE DATA ACROSS VOLTAGE RANGE OF THE CIRCUIT SHOWN IN FIGURE 1

	110 V _{AC}	120 V _{AC}	130 V _{AC}
I _{RMS(IN)} (mA)	64.00	66.07	69.33
PF	0.9911	0.9923	0.9931
THD (I _{RMS} , %)	13.01	12.02	11.52
P _{IN} (W)	6.99	7.88	8.90
Efficiency (%)	82.9	78.6	75.0

Dimming Compatibility

Table 3. THE CIRCUIT DIMMED SMOOTHLY AND HELD OPERATION WITH NO FLICKER, FLASHES, ETC. WITH THESE AVAILABLE DIMMERS

Manufacturer	Serial Number
Lutron	500–15591A
Lutron	TGCL–153PH
Lutron	Skylark CTCL–153PDH
Pass & Seymour	450 W – CFL/LED
Leviton	IPL06–10Z
Leviton	6674–POW
Lutron	SCL–153P
Lutron	AYCL–153P

Representational Circuit Diagrams

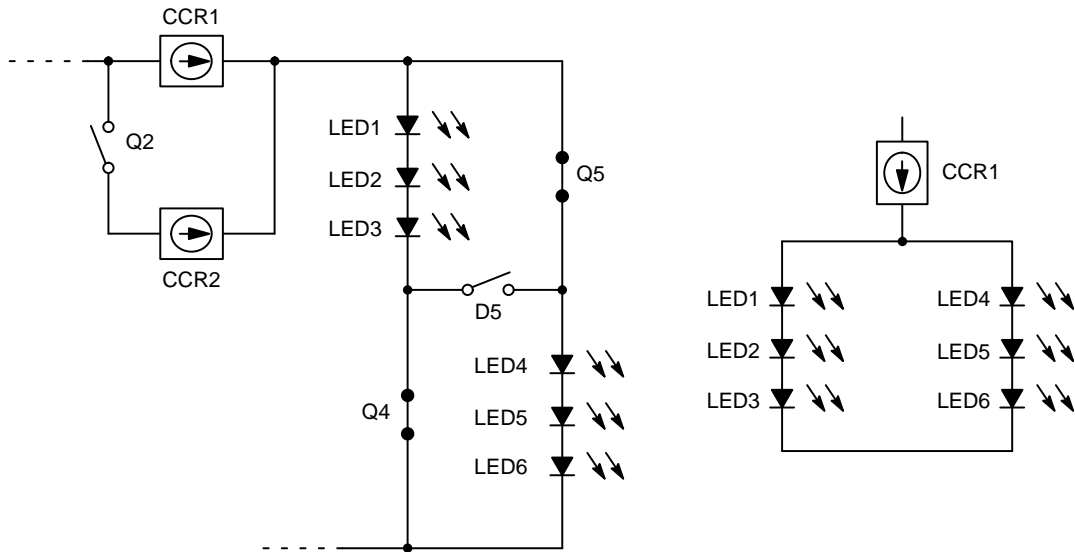


Figure 2. Stage 1, showing parallel configuration of LEDs and single CCR. Transistors Q4 and Q5 are on, and the D5 routing diode is reverse-biased. The LEDs are in parallel below the CCR and split the regulated current. The driver is in this configuration at bridge outputs below 122 V.

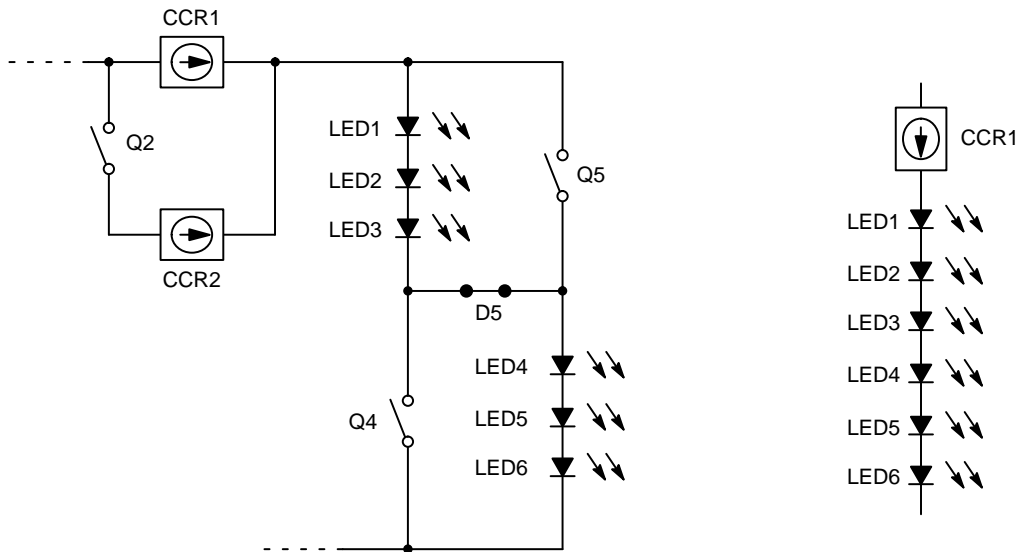


Figure 3. Stage 2, showing series LED configuration and single CCR operation. Transistors Q5 and Q6 are switched off and current flows through the D5 routing diode, enabling series configuration. The driver is in this configuration at bridge outputs between 122 V and 124 V.

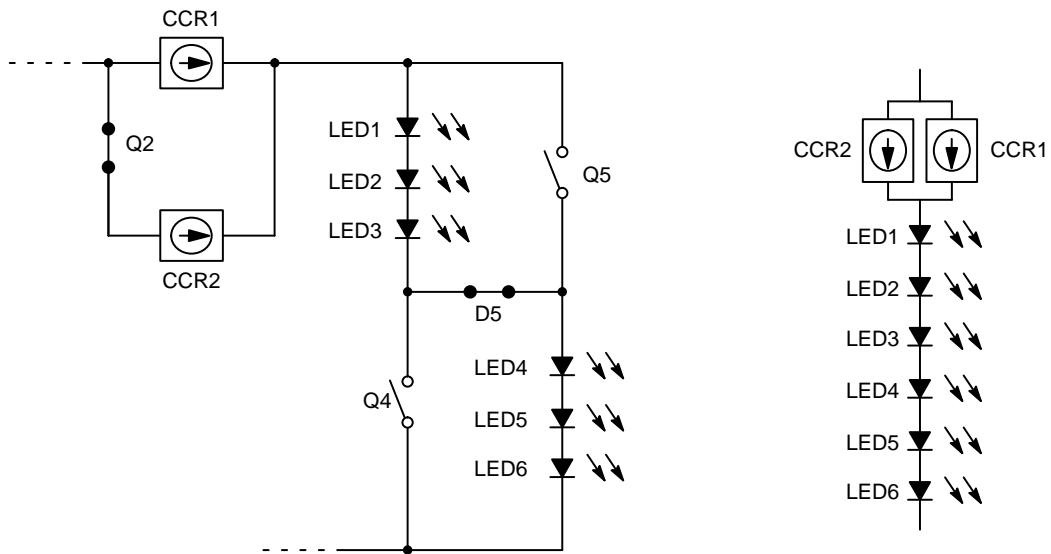


Figure 4. Stage 2, showing two parallel CCRs driving an LED series configuration. This occurs at bridge outputs above 124 V after the transistor Q2 has saturated.

Waveforms

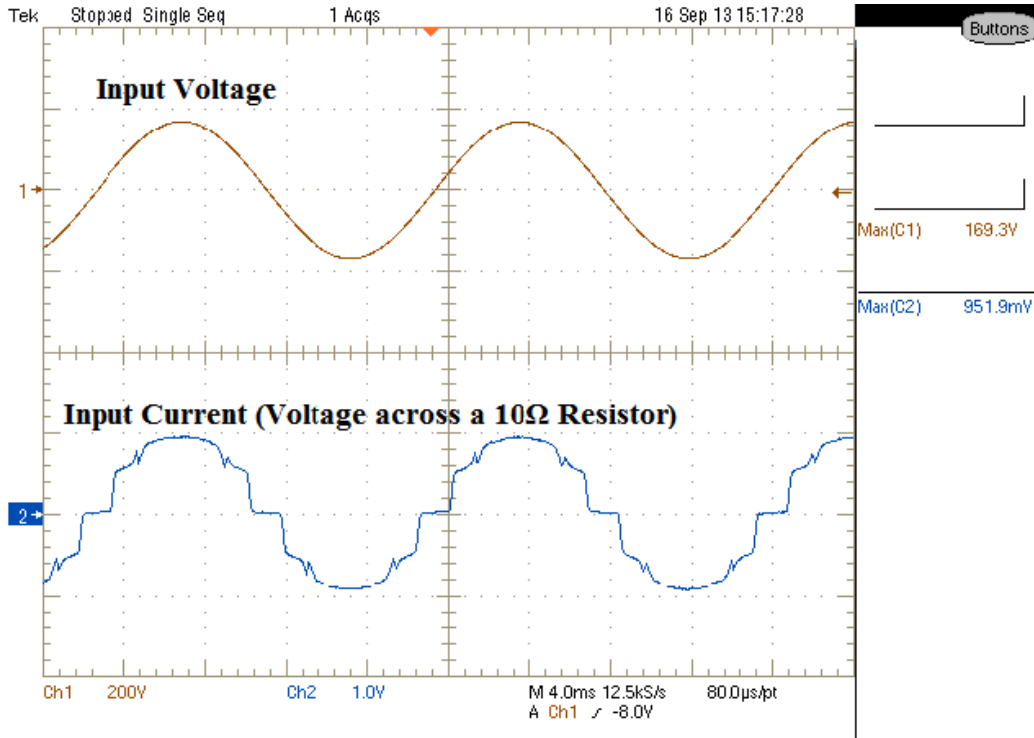


Figure 5. Transient capture of the total input voltage and current waveforms. Note the sinusoidal shape of the input current closely follows the voltage, resulting in good PF and THD performance.

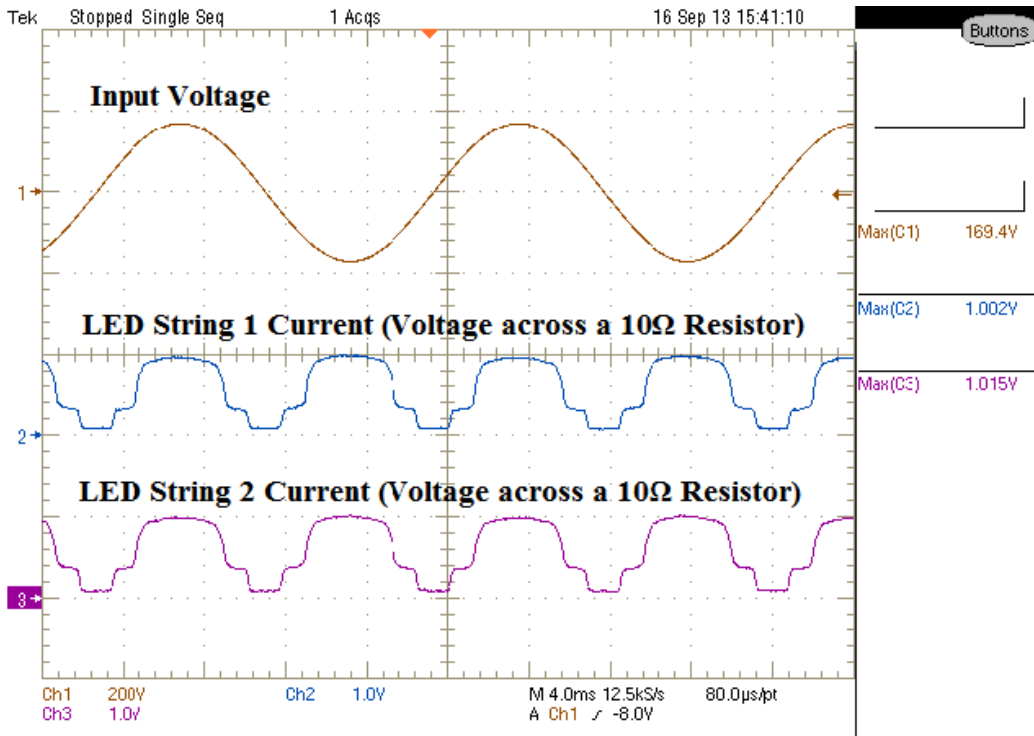


Figure 6. LED currents through both strings. LED String 1 contains LED1 through LED3, and String 2 contains LED4 through LED6. Note the identical current waveforms and the two distinct levels in current, corresponding to the parallel/series LED configurations.

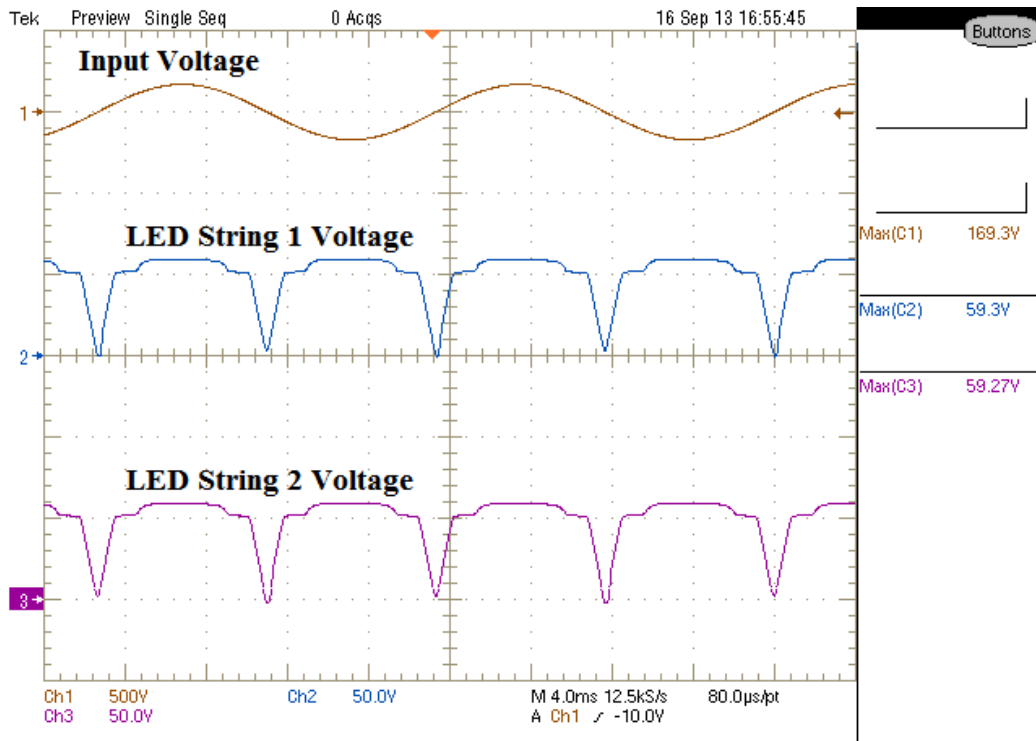


Figure 7. LED string voltages are equal at all times. The distinct levels in forward voltage are a result of the different LED current levels in the two stages of operation. Given an LED string V_f of 60 V, the LEDs are on about 81% of the time.

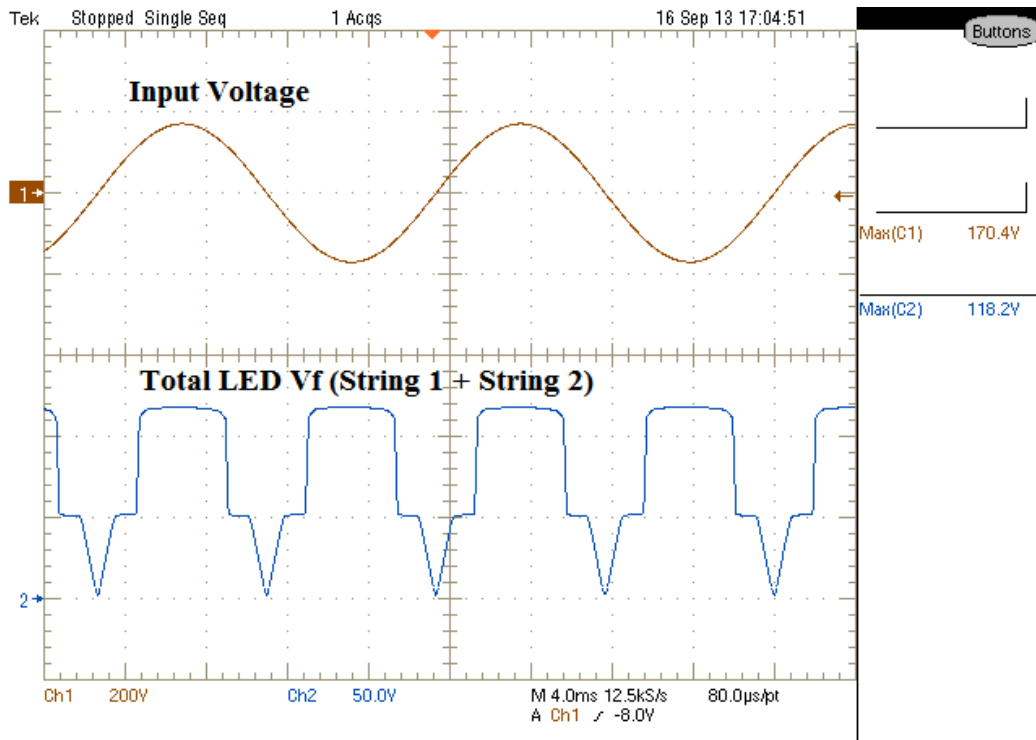


Figure 8. Total LED voltage. Measured from the anode of LED1 to the cathode of LED6 (bridge ground), the parallel and series configurations of the LEDs can be seen. The LEDs spend most of their time in the series configuration.

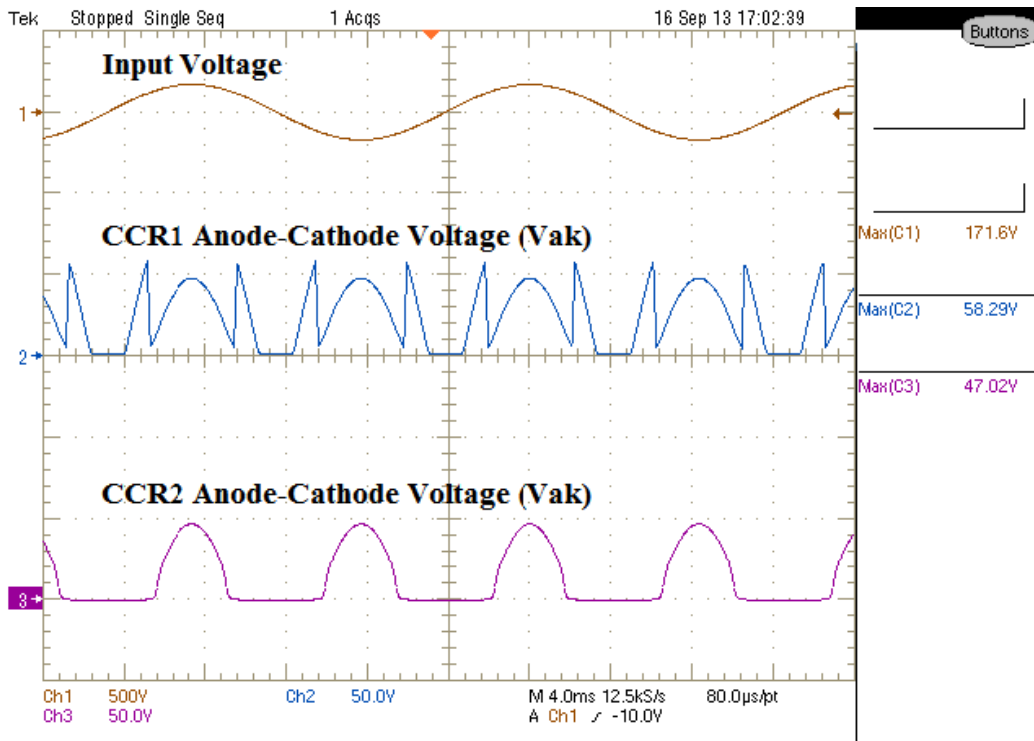


Figure 9. Anode-Cathode voltages for both CCRs. The sharp valleys in the CCR1 waveform are where the LED voltage increases, which reduces the V_{ak} across the device. CCR2 is left off until the bridge voltage is high and the LEDs are in series configuration.

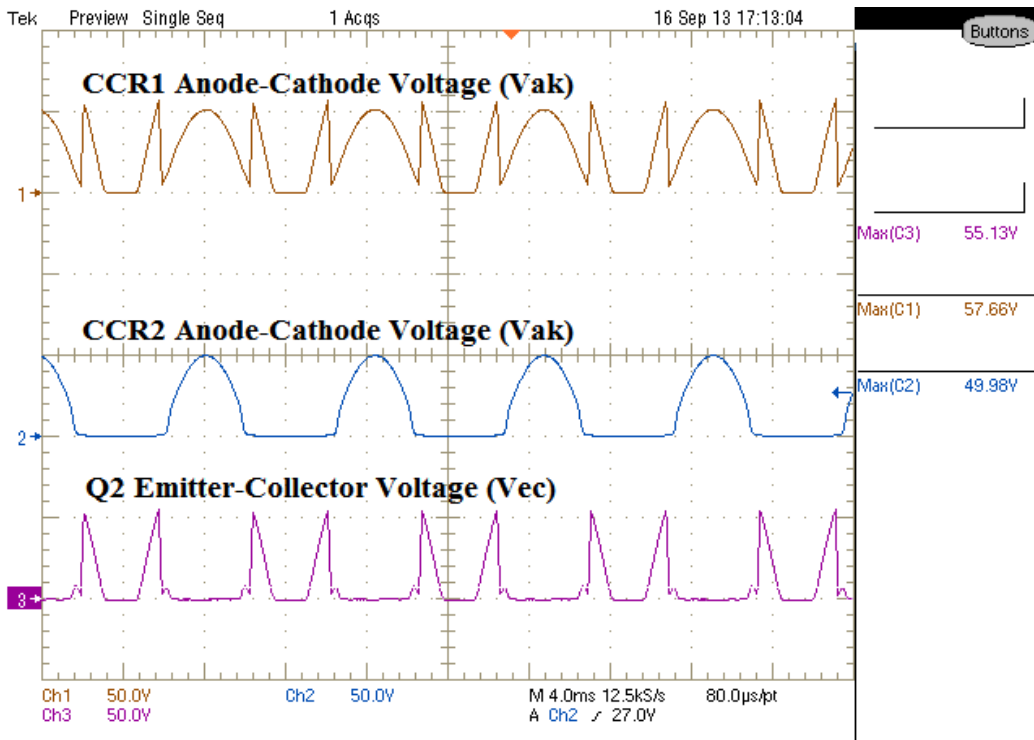


Figure 10. Q2 and CCR2 are in series, together paralleled with CCR1. Q2 blocks CCR2 from conducting during the parallel mode of operation, and after entering saturation, allows CCR2 to conduct.

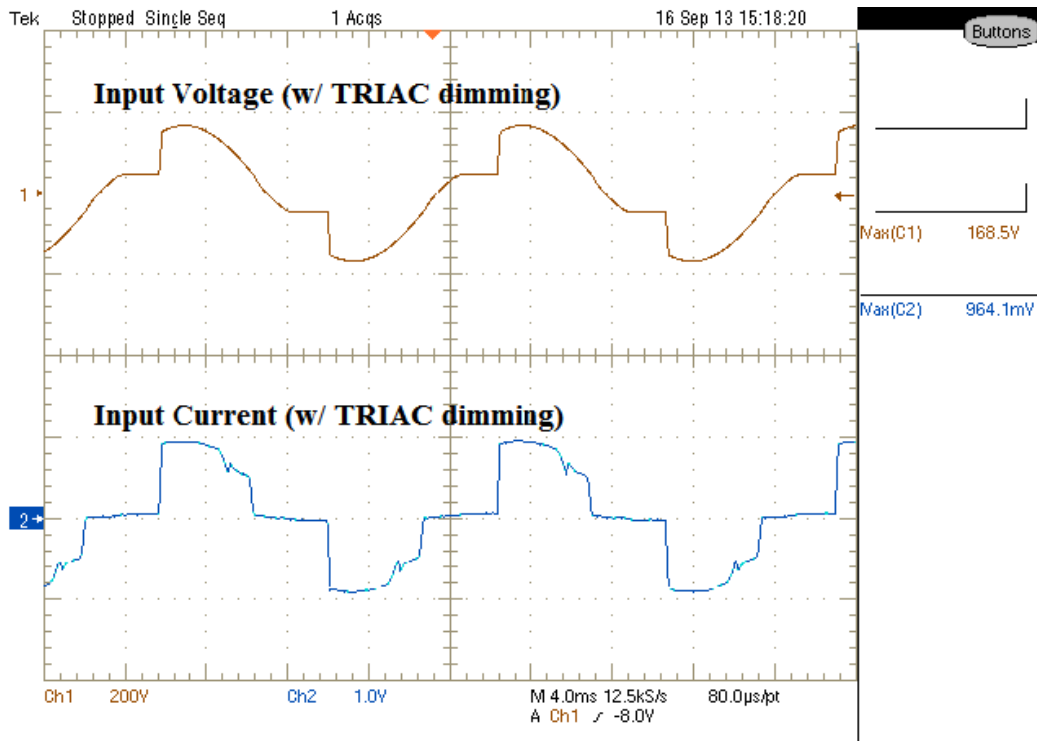


Figure 11. The circuit receives no current when the TRIAC is off, and the general shape of the input current waveform is preserved when the TRIAC is on.

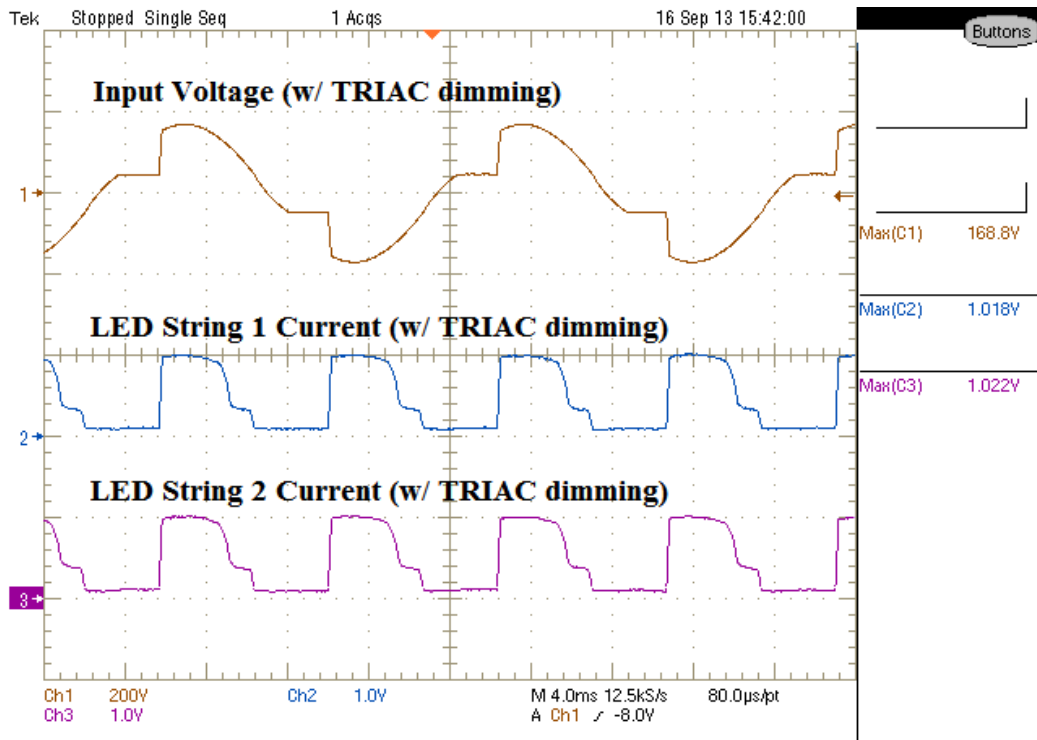


Figure 12. LED current turns off when the TRIAC is off, and the currents are identical every half-cycle, resulting in smooth, flicker-free dimming.

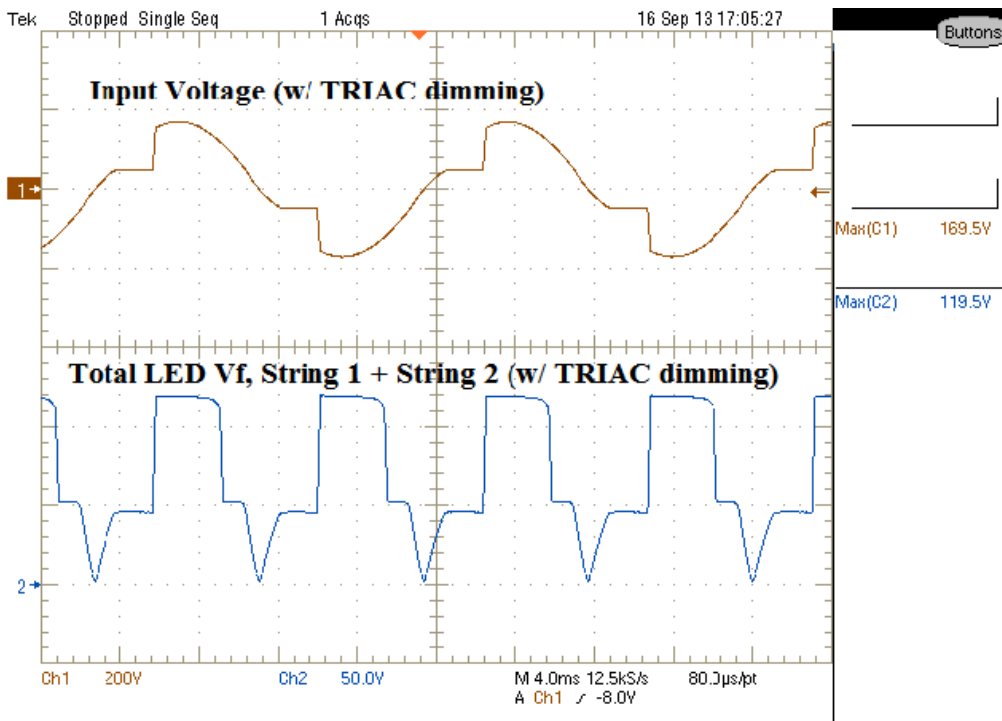


Figure 13. The LED total voltage continues to switch between parallel and series configurations normally, even with a TRIAC. The LEDs are off while the TRIAC is off.

Design Modifications

When altering the LED load, the driver’s switching behavior must be adjusted to match the voltage levels of the LED load. The plot below is a ball park (additional optimization may yield better performance) for the value of

the switching resistor (R2) as a function of LED string voltage to expedite design. This curve is based on the $V_{SWITCH(Q1)}$ equation on page 2. Finding the optimal switching resistors is important for maximizing efficiency and minimizing THD.

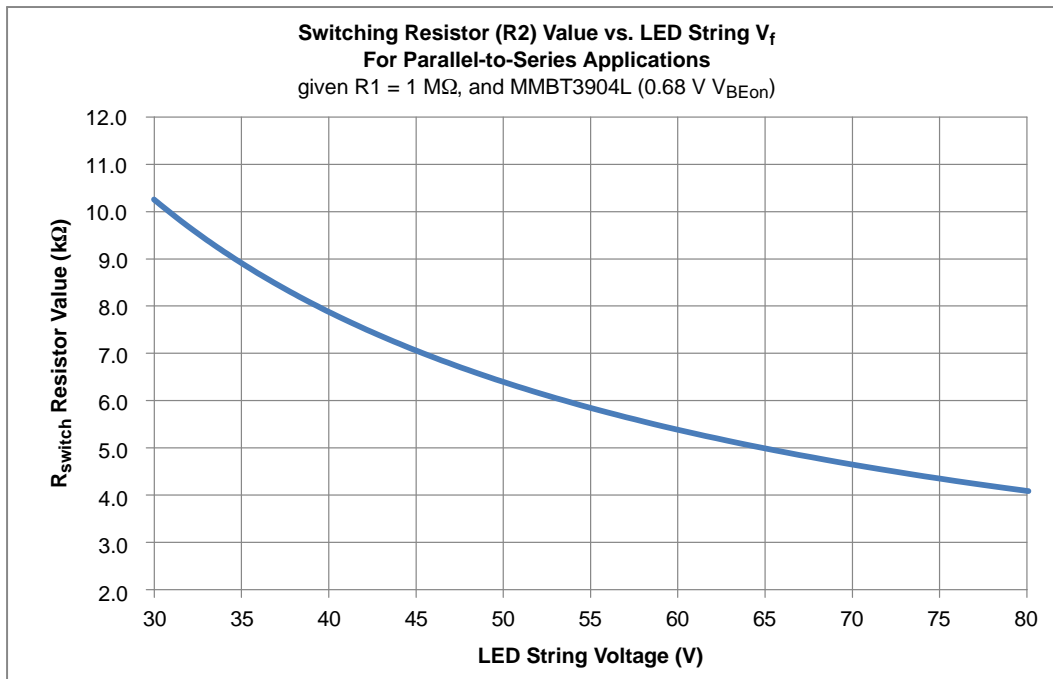


Figure 14. Plot showing suggested switching resistor value as a function of LED string voltage. The driver is tunable for strings between 30 and 80 V_f .

DN05052/D

For higher power levels, additional CCRs may be added in parallel with CCR1 at little cost to performance. Below is data taken of performance parameters while sweeping CCR1 and increasing LED power. As the circuit power

increases, additional optimization may be useful to help reduce THD, such as reducing the R2 switching threshold resistor value.

Table 4. PERFORMANCE EVALUATING AT VARIOUS CCR CONFIGURATIONS

CCR Config (CCR1 + CCR2)	Power Factor	Input Power	Output Power (Pin * 79%)	THD (% Arms)	Input Current
50 + 30 mA (Original)	0.992	7.9 W	6.2 W	12.0%	70 mA _{rms}
80 + 30 mA	0.987	11 W	8.7 W	15.4%	93 mA _{rms}
100 + 30 mA	0.985	12.8 W	10.1 W	16.8%	105 mA _{rms}
130 + 30 mA	0.982	15.7 W	12.4 W	18.8%	134 mA _{rms}

Changing CCR2 requires redesigning the R4/R5/Q2 turn-on circuitry, and for higher power levels (or switching on higher CCR2 currents), a structure like the R4–R7, Q2–Q3 structure in DN05063/D is more scalable.

Evaluation Board

The evaluation kit CCR120PS3GEVK implements this circuit on metal-clad board and includes a driver and LED boards. If the user desires to use their own LEDs, the driver board may be obtained singularly via the CCR120PS3AGEVB evaluation board (driver circuitry, pictured left). Note that the R2 resistor must be changed as according to Figure 14, and the formulas on page 2.

Circuit Data

Table 5. USING METAL-CLAD EVALUATION BOARD

	110 V _{AC}	120 V _{AC}	130 V _{AC}
I _{RMS(IN)} (mA)	65.72	67.72	68.69
PF	0.9915	0.9927	0.9931
THD (I _{RMS} , %)	12.89	11.88	11.53
P _{IN} (W)	7.18	8.10	8.95
Efficiency (%)	81.4	77.2	72.6

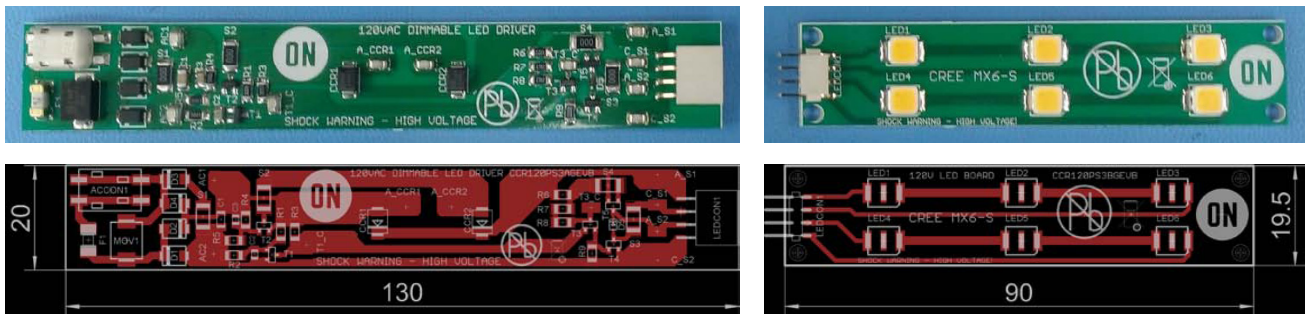


Figure 15. Driver and LED Boards

DN05052/D

Bill of Materials

Table 6. BILL OF MATERIALS, AS DESIGNATED BY FIGURE 1 SCHEMATIC


Designator	Qty	Description	Value	Tolerance	Manufacturer	Part Number
CCR1	1	Constant Current Regulator	120 V, 50 mA	±15%	ON Semiconductor	NSIC2050JB
CCR2	1	Constant Current Regulator	120 V, 30 mA	±15%	ON Semiconductor	NSIC2030JB
F1	1	Fuse	250 V, 1 A	–	Any	–
MOV1	1	Varistor	150 V	–	Any	–
D1–D4	4	Diode	400 V, 1 A	–	ON Semiconductor	MRA4004
D5	1	Diode	75 V, 200 mA	–	ON Semiconductor	BAS16H
C1	1	Capacitor	2.2 nF, 200 V	–	Any	–
C2	1	Capacitor	1 nF, 10 V	–	Any	–
R1	1	Resistor	1 MΩ, 1/8 W	±1%	Any	–
R2	1	Resistor	5.6 kΩ, 1/8 W	±1%	Any	–
R3	1	Resistor	301 kΩ, 1/8 W	±1%	Any	–
R4	1	Resistor	590 Ω, 1/8 W	±1%	Any	–
R5	1	Resistor	100 kΩ, 1/8 W	±1%	Any	–
R6, R9	2	Resistor	2.2 kΩ, 1/8 W	±1%	Any	–
R7, R8	2	Resistor	27 kΩ, 1/8 W	±1%	Any	–
Q1	1	NPN Transistor	40 V, 200 mA	–	ON Semiconductor	MMBT3904L
Q2, Q5	2	PNP Transistor	150 V, 500 mA	–	ON Semiconductor	MMBT5401L
Q3	1	NPN Transistor	350 V, 100 mA	–	ON Semiconductor	MMBT6517L
Q4	1	NPN Transistor	140 V, 600 mA	–	ON Semiconductor	MMBT5550L
LED1–LED6	6	LEDs	20 V, 175 mA	–	Any	–

Further References

For similar 120 V_{AC} LED lighting solutions with CCRs, please refer to these other design notes:

- Design Note – [DN05046/D](#): 120 V_{AC}, Low-Cost, Dimmable, Linear, Parallel-to-Series LED Driving Circuit
- Design Note – [DN05063/D](#): 2-Stage Parallel-to-Series, ENERGY STAR[®] Low-Cost Linear LED Driver Design

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