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DN05051/D

120 V_{AC}, Dimmable, Linear 3-stage, Parallel-to-Series LED Lighting Circuit

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DESIGN NOTE

Table 1. DEVICE DETAILS

Device	Application	Topology	Efficiency	Input Power	Power Factor	THD
NSIC2030JB, NSIC2050JB	AC LED Lighting	Linear	82%	7.8 W	0.99	13.6%

Overview

This circuit uses inventive techniques to provide a cost-efficient and effective AC LED lighting solution for 120 V_{AC} mains power. Its primary features are its high efficiency, dimmability, high light output, high power factor, and low THD.

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

The circuit uses a parallel-to-series topology that dynamically adjusts LED forward voltage (V_f) to match the bridge output voltage for high efficiency.

The circuit employs ON Semiconductor Constant Current Regulators (CCRs) to regulate LED current and protect LEDs from over-voltage conditions. The circuit also utilizes an additional CCR to increase LED current at high voltages to improve PF and THD.

Key Circuit Features

- Functional with Wide Range of Standard Phase-Cut TRIAC Dimmers
- Low-Cost
- PF = 0.99
- Efficiency > 80% Over Voltage Range
- THD < 15%
- Adjustable for Different LED Voltages
- Adjustable for Different Currents/Power Levels

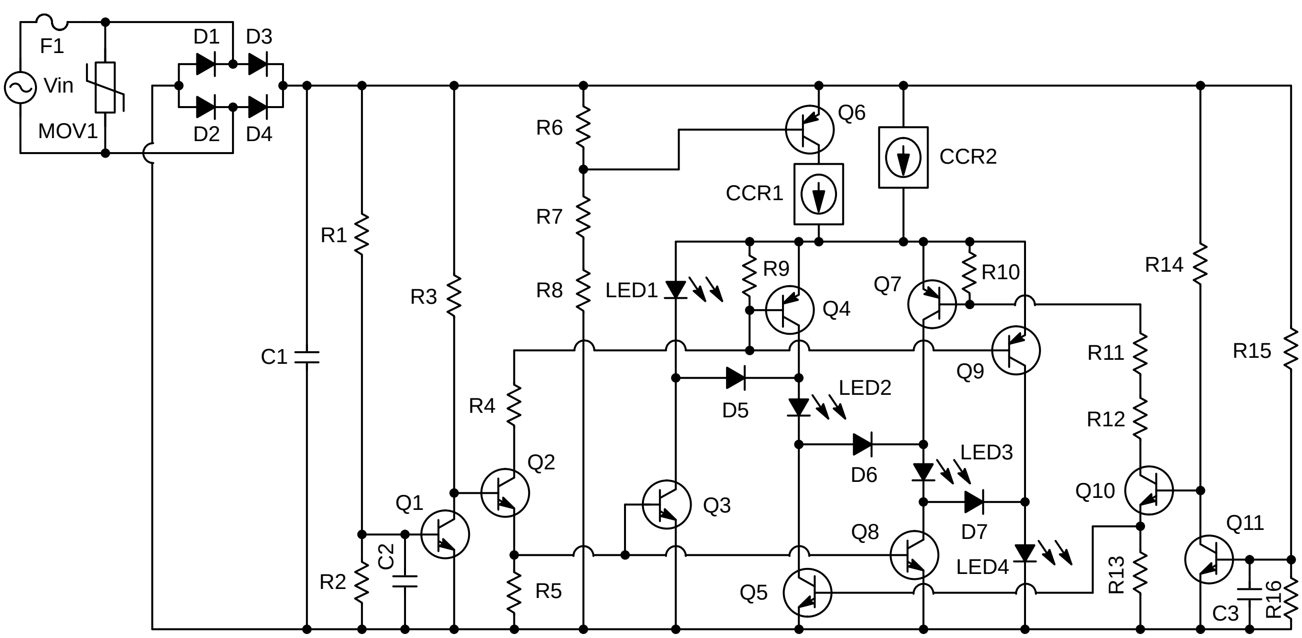

Figure 1. 3-stage Parallel-to-Series LED Lighting Circuit

Circuit Description

The circuit consists of a full-wave bridge rectifier (D1–D4), parallel-to-series switching circuitry (R1–R5, R9–R16, C1–C3, Q1–Q5, Q7–Q11), CCR turn-on circuitry (R6–R8, Q6), CCRs (CCR1–CCR2), LED routing diodes (D5–D7), and LEDs (LED1–LED4).

Circuit Operation

The bridge rectifier outputs a half-wave sine peaking at about 170 V (for 120 V_{AC}). This bridge output is referenced between the cathodes of D3 and D4 to the anodes of D1 and D2.

The circuit dynamically adjusts the LED V_f to closely resemble the rectified half-sine output of the full-wave bridge. As seen in the "Representational Circuit Diagrams" section, the LEDs change between three configurations with varying bridge output.

The first configuration, when the bridge output is between 0 V and 72 V†, is a "parallel" stage, when all LEDs are in parallel with each other. CCR2 is on, as well as all the Q3 through Q5 and Q7 through Q9 transistors. The D5, D6, and D7 diodes are all reverse-biased. CCR current (when above the LED V_f turn-on voltage of 36 V) is split down the four strings of LEDs.

The second configuration, when the bridge output is between 72 V and 145 V††, shifts the LEDs into two parallel strings. Q1 initiates the transition into the second stage switching on at 72 V due to the R1/R2 voltage divider. When Q1 turns on, Q2's V_{BE} is shorted, eliminating base current for transistors Q3, Q4, Q8, and Q9. As these turn off, the D5 and D7 diodes are forward biased, connecting LED1 to LED2, and LED3 to LED4. D6 is still reverse-biased.

The third stage, when the bridge output is above 145 V, puts all the LEDs in one series string. Q11 turns on by the R15/R16 voltage divider and initiates this transition. Q11 turns off Q10, which then deprives Q5 and Q7 of base current, turning them off as well. D6 becomes forward-biased, and all the LEDs pass CCR2's current.

After the LEDs are all in series, CCR1 is set to turn on to provide additional current at high voltages. This matches the total current waveform to the input voltage waveform, achieving better power factor and THD performance. With about an extra 7 V over the device, CCR1 is in full regulation at about 152 V bridge output.

† This switching voltage is determined by the R1/R2 resistor divider and the $V_{BE(sat)}$ of the transistor used − in this case, an ON Semiconductor MMBT3904L NPN BJT. A typical value for $V_{BE(sat)}$ at 25°C is roughly 0.68 V. The switching voltage may be found using the following equation:

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

Using the values R1 = 1 MΩ, R2 = 9.53 kΩ, $V_{SWITCH(Q1)}$ = 72 V.

†† Similar to the $V_{SWITCH(Q1)}$ relationship, Q11 is triggered on by the R15/R16 resistor divider. Also an ON Semiconductor MMBT3904L, the expected $V_{BE(sat)}$ of Q11 is roughly 0.68 V, and by the following equation:

$$V_{SWITCH(Q11)} = V_{BE(sat)} \cdot \left(\frac{R15 + R16}{R16}\right)$$

Using the values R15 = 1 MΩ, R16 = 4.7 kΩ, $V_{SWITCH(Q11)}$ = 145 V.

Design Modifications

Special modifications for this circuit might include LED string forward voltage (V_f) and CCR1 current value. For optimal performance, it is recommended that LED strings of V_f between 15 V and 40 V are used. Generally, the higher the LED V_f, the greater the efficiency, though the benefits of PF/THD-improving CCR1 are reduced. The lower the V_f, the lower the efficiency and the earlier the LEDs will turn on. Note that changing LED V_f will require R2 and R16 to be changed to adjust switching points.

If a higher CCR1 value is desired, a darlington-connected PNP pair or PFET is recommended in place of Q6 to reduce base current and increase gain. Multiple CCRs may be used in parallel with CCR2 to no adverse effect, only ensure that R4, R11, and R12 allow sufficient base current.

Circuit Performance Data

Table 2. ELECTRICAL CHARACTERISTICS FOR THE CIRCUIT SHOWN IN FIGURE 1

	110 V_{AC}	120 V_{AC}	130 V_{AC}
$I_{RMS(IN)}$ (mA)	64.39	65.49	66.06
PF	0.9886	0.9907	0.9921
THD (I_{RMS}, %)	14.86	13.56	12.35
P_{IN} (W)	6.93	7.75	8.44
Efficiency (%)	80.4	82.2	81.0

Product parametric performance is indicated in the Electrical Characteristics for the listed test conditions, unless otherwise noted. Product performance may not be indicated by the Electrical Characteristics if operated under different conditions.

Dimmers Tested

Table 3. THE CIRCUIT WAS FULLY FUNCTIONAL WITH EACH DIMMER TESTED

Manufacturer	Serial Number
Leviton	600W−1D4102
Leviton	600W−1B4105
Lutron	Skylark CTCL−153PDH
Lutron	TG−600P−AC

Representational Circuit Diagrams

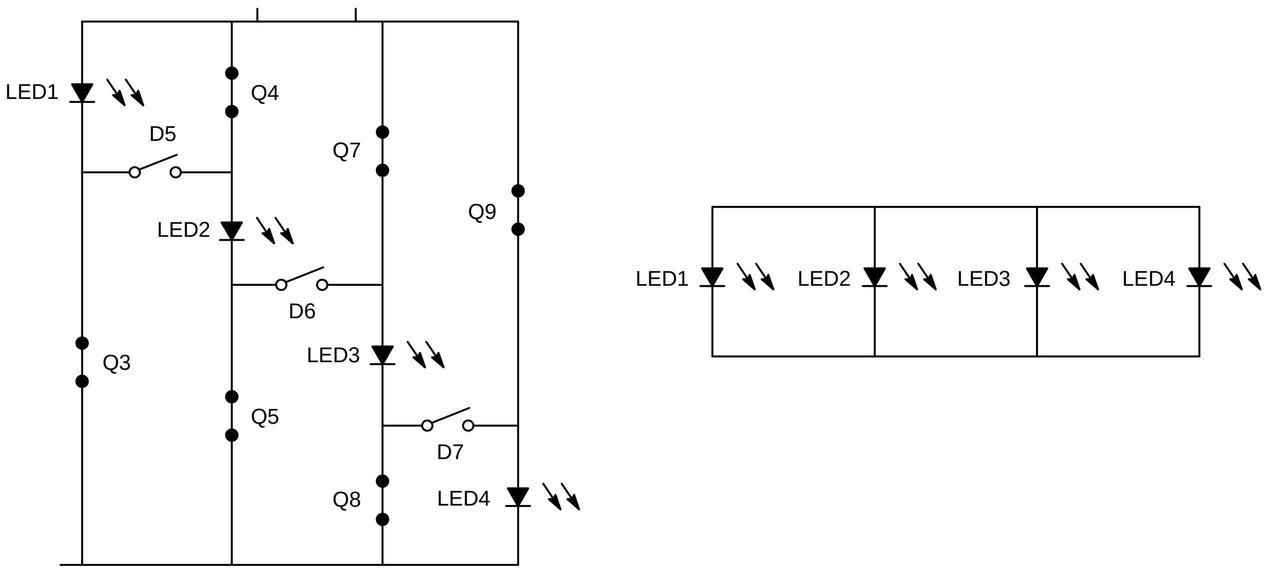

Figure 2. Stage 1/Parallel configuration of LEDs, showing behavior of switching circuitry. D5−D7 are open circuits, whereas all the transistors Q3–Q5 and Q7–Q9 are on. The LEDs are then in parallel below the CCR. The driver is in this state at bridge voltages below 72 V

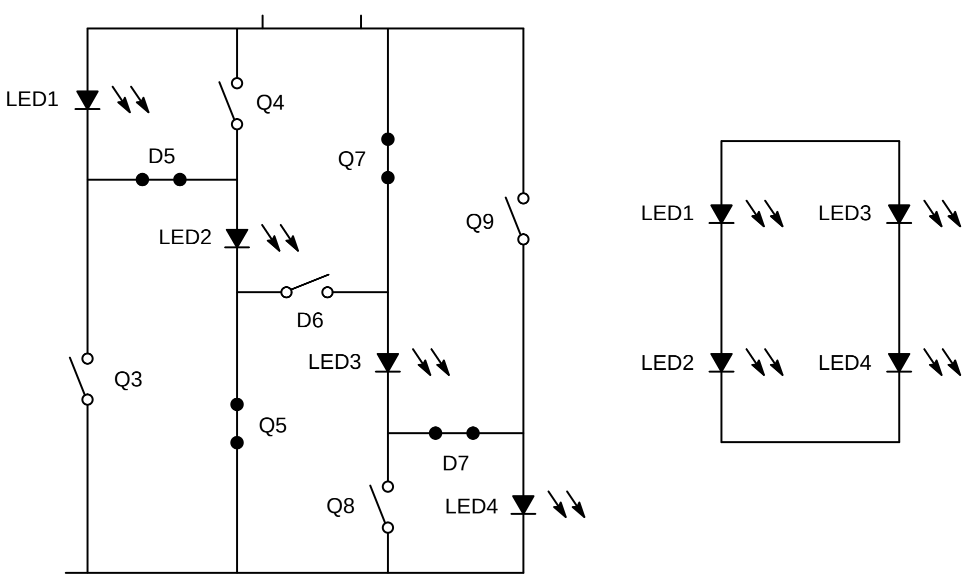

Figure 3. Stage 2/Parallel-Series configuration of LEDs. Transistors Q3–Q4 and Q8–Q9 are open, and current flows through the routing diodes D5 and D7. Simplified schematic containing only the LEDs is shown to the right. The driver is in this state between 72 V and 145 V

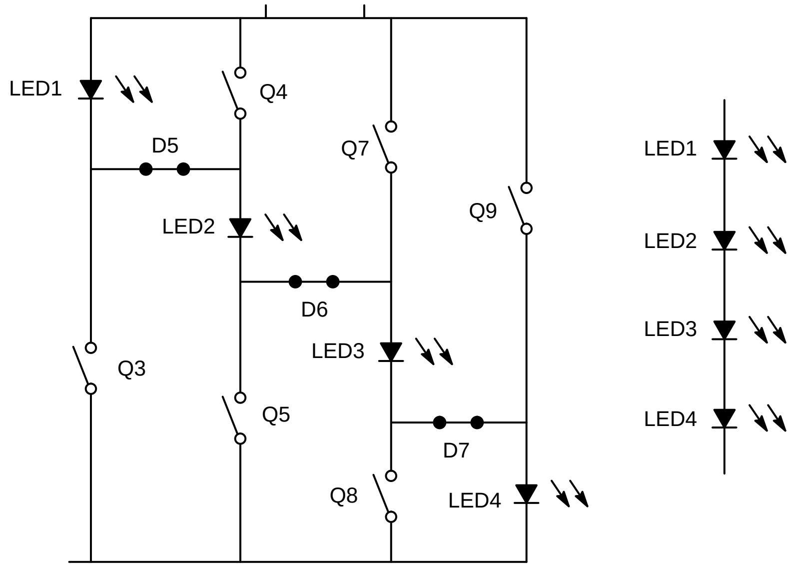

Figure 4. Stage 3/Series configuration of the LEDs and switching circuitry shown. All transistors Q3–Q5 and Q7–Q9 are off at high bridge voltages, and current passes through the routing diodes D5–D7. The driver is in this stage at bridge voltages above 145 V

Waveforms

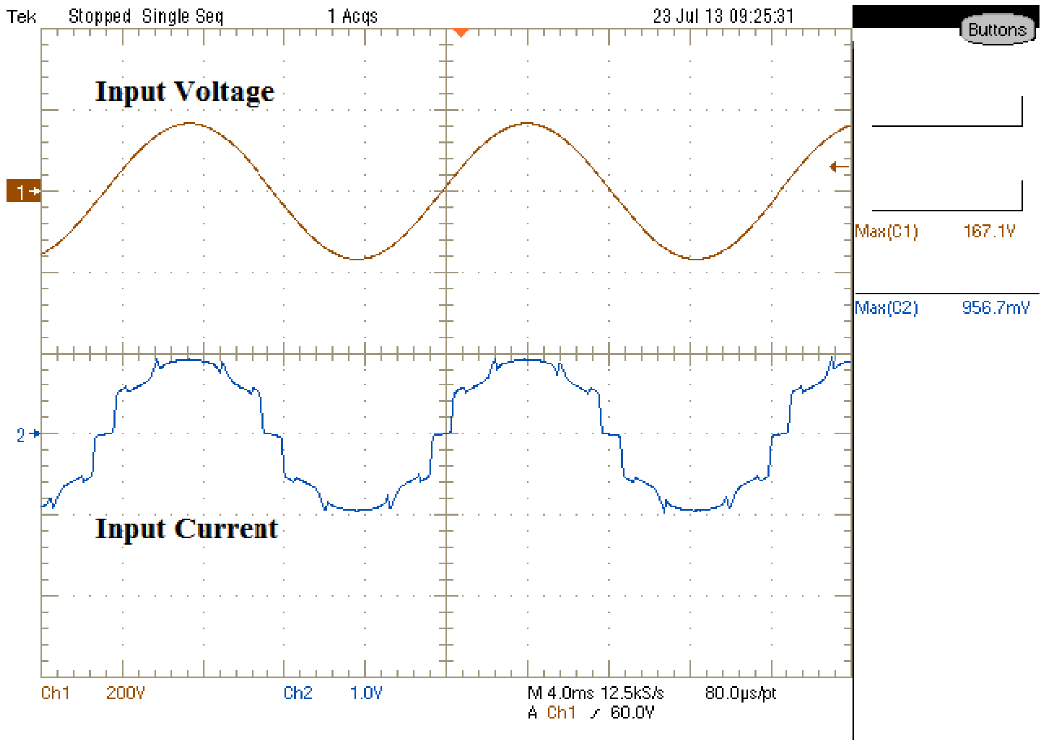

Figure 5. The total input current follows the voltage waveform very closely, yielding high power factor and outstanding THD performance

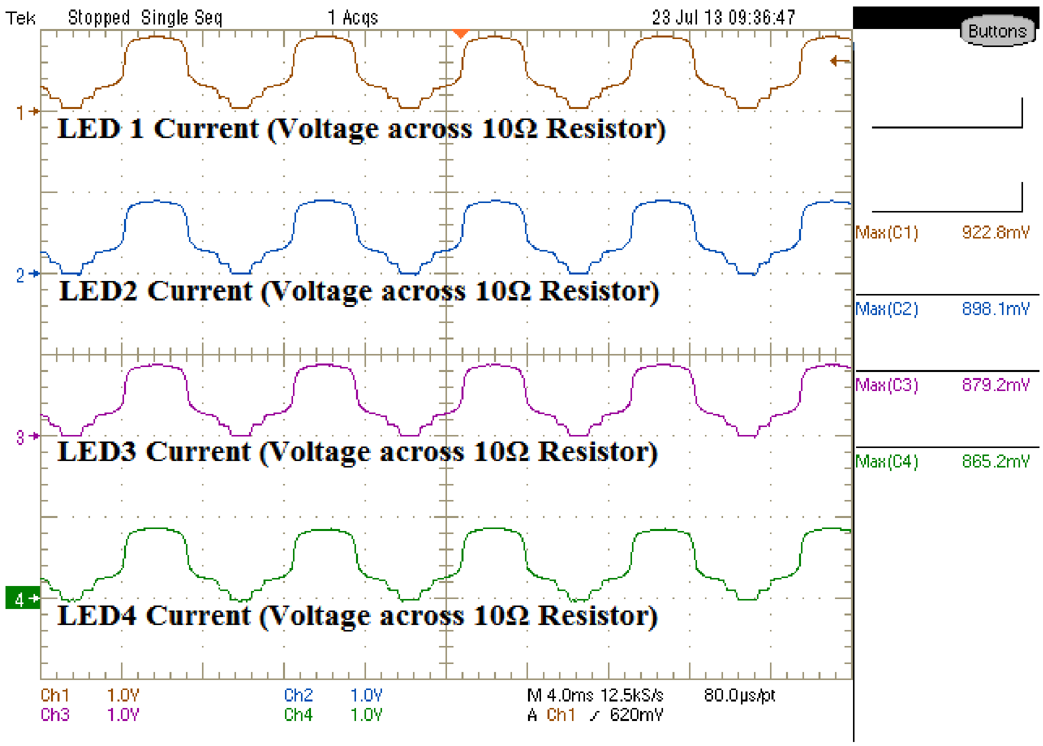

Figure 6. LED current through each of the LEDs. Note the current waveforms are nearly identical, as well as the three distinct levels of current, coinciding with the three LED configurations

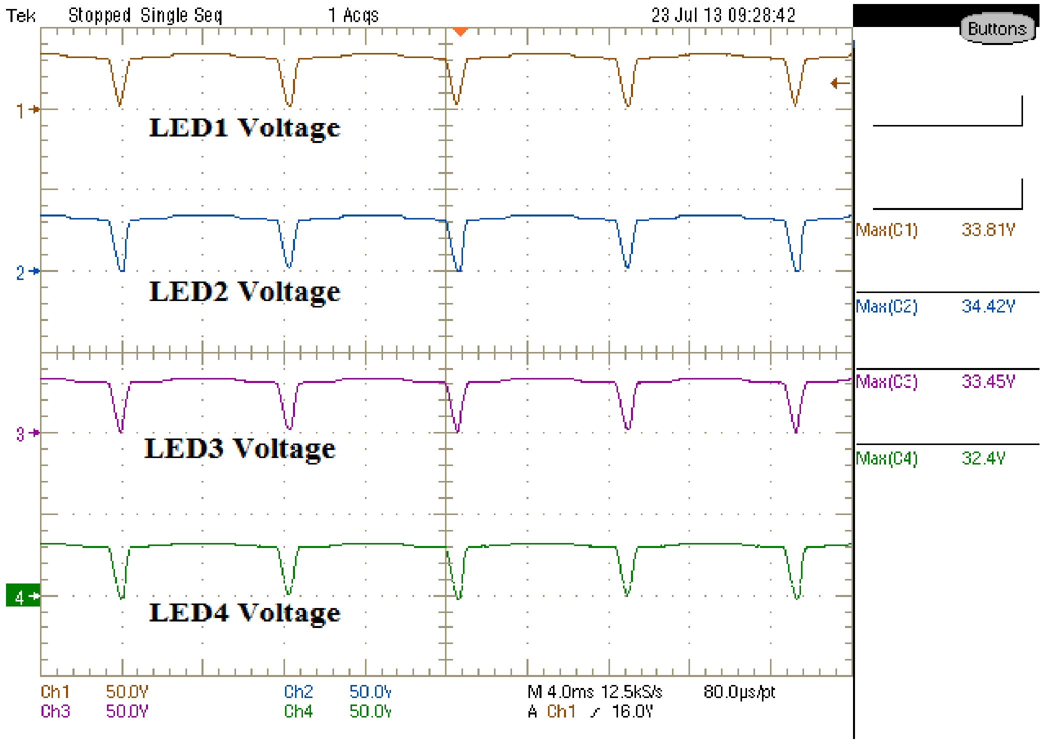

Figure 7. The LED forward voltage is identical for all LEDs. When the LED voltage is not 0 V, the LEDs are on. Given an LED V_f of 32 V, the LEDs are on about 92% of the time

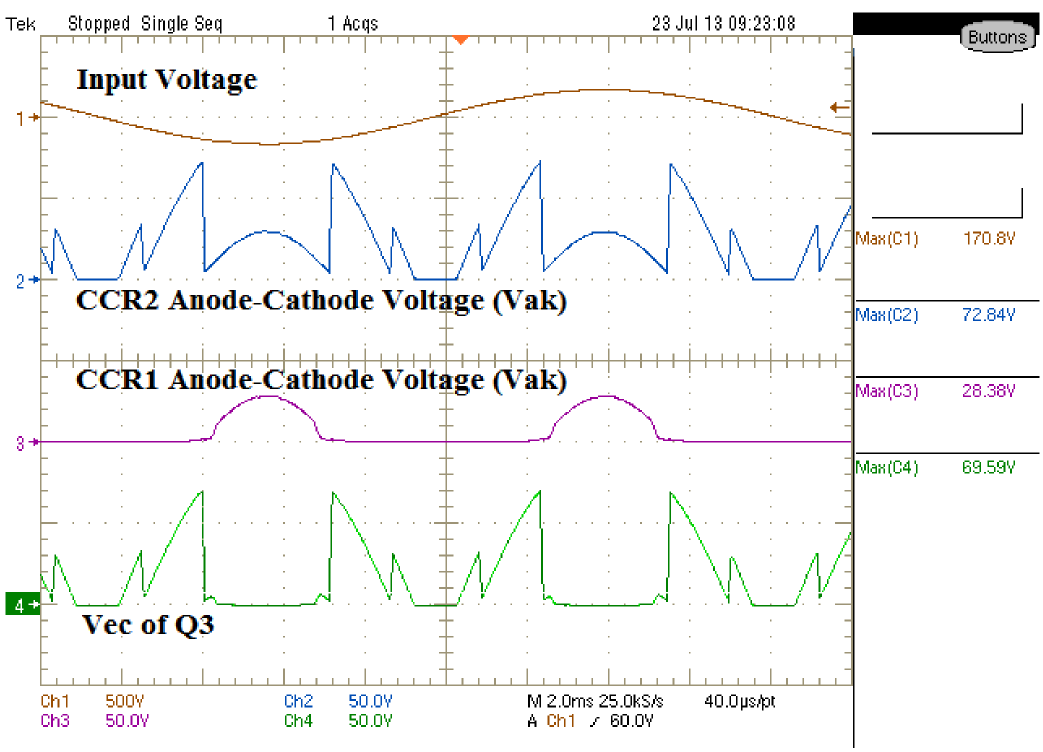

Figure 8. The CCR2 V_{ak} demonstrates the different stages of the LED configurations. Q3 blocks CCR1 from conducting only until the highest bridge voltages. Q3 and CCR1 are in parallel with CCR2

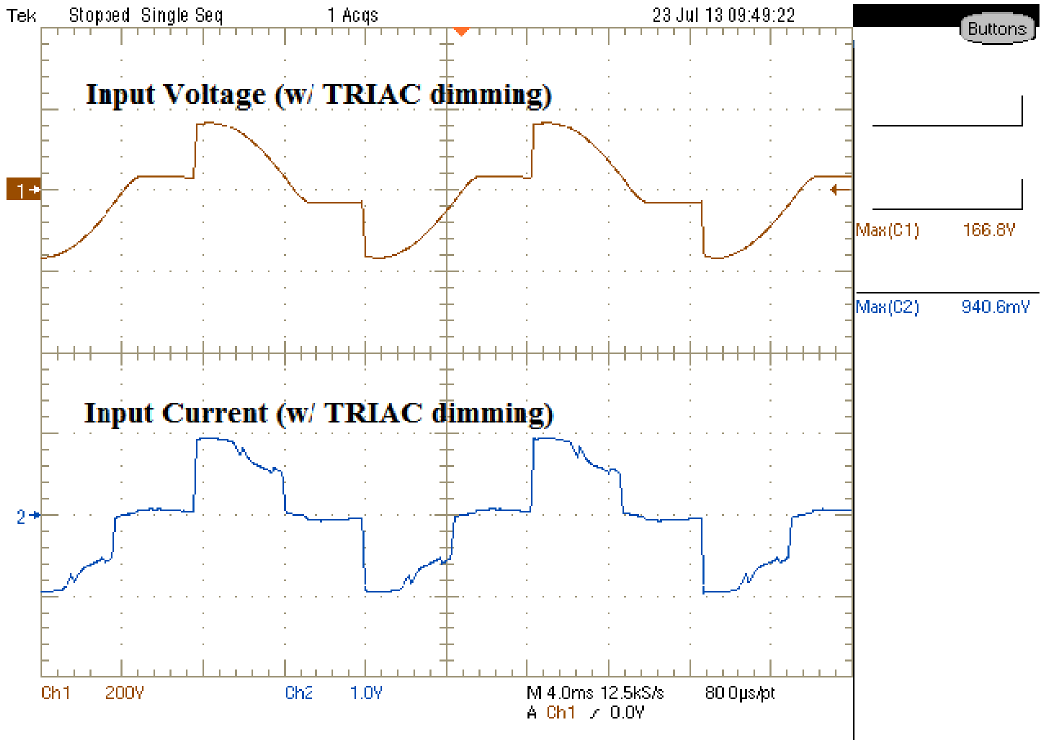

Figure 9. The circuit receives no input current when the TRIAC is off, and the current is normal when the TRIAC is on

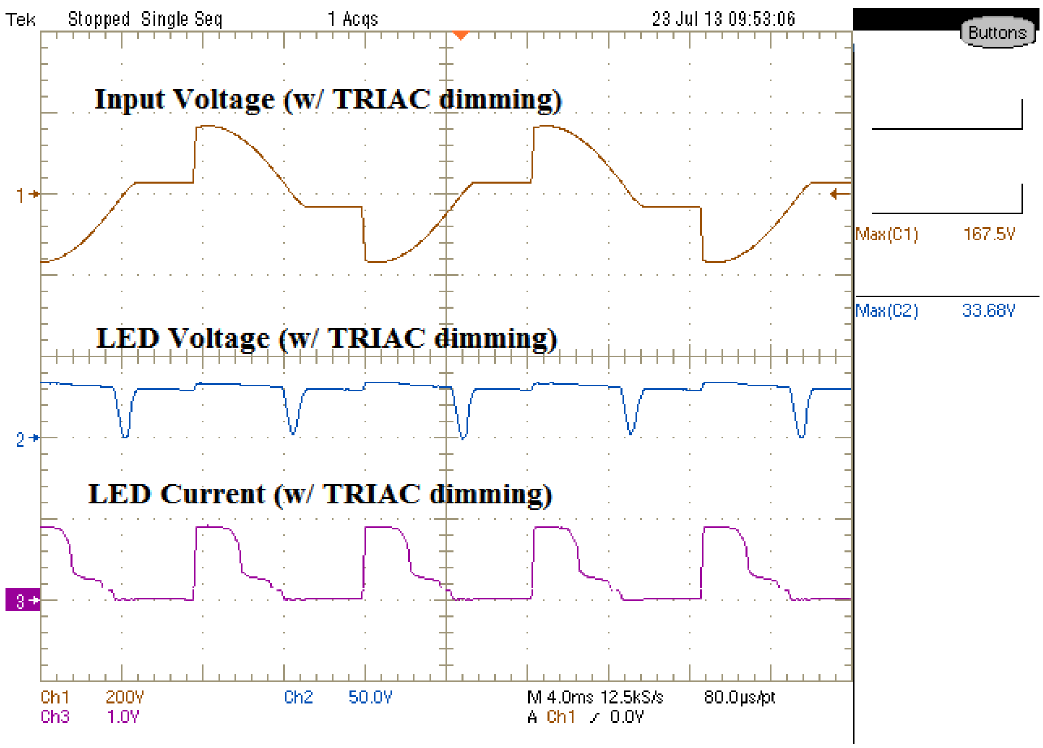

Figure 10. LED1's voltage and current waveforms, unaffected by TRIAC dimming. The voltage on the LEDs is due to the non-zero voltage out of the dimmer during the "off" state

Evaluation Board

The evaluation board CCR230PS3AGEVB (driver circuitry, pictured below) may be altered from its original design for 230 V_{AC} to replicate the performance of this circuit at 120 V_{AC}.

Figure 11. CCR230PS3AGEVB Evaluation Board with Changes Marked for DN05051/D

A list of modifications appears below, along with data taken using the metal-clad board. Overall circuit performance is greatly improved when using metal-clad boards.

Table 4. LIST OF MODIFICATIONS

CCR230PS3AGEVB Reference	Recommended Modification	Alternative Modification	DN05051/D Designator
R3	Replace with 9.53 kΩ	Desired R_{set1} Value	R2
R10	Replace with 4.7 kΩ	Desired R_{set2} Value	R16
R15	Replace with 255 Ω	Parallel with 309 Ω	R6
R16	Replace with 24.9 kΩ	Parallel with 28 kΩ	R7
R17	Replace with 24.9 kΩ	Parallel with 28.7kΩ	R8
CCR1	Replace with NSIC2030JBT3G	–	–

Circuit Data

Table 5. USING REFITTED EVALUATION BOARD

	110 V_{AC}	120 V_{AC}	130 V_{AC}
$I_{RMS(IN)}$ (mA)	61.05	65.03	67.86
PF	0.9864	0.9890	0.9907
THD (I_{RMS}, %)	16.5	14.42	13.02
P_{IN} (W)	6.64	7.75	8.76
Efficiency (%)	84.1	83.3	80.1

Design Modifications

If the user wishes to connect their own LEDs to the evaluation board, it should be noted that the off-board connections (in keeping with the design note's designators) will be as shown in Figure 12.

It should also be noted that different LED voltages will require you to adjust switchpoints for best performance. A reference plot (Figure 13) showing recommended values for switching resistors R2 and R16 is also given, as a function of LED string voltage.

Of course, optimizing the system may require some experimentation, but the plot is provided as a ballpark design tool. With this design, four strings between 15 V_f and 40 V_f are recommended, for a total of 60 to 160 V_f total of LEDs.

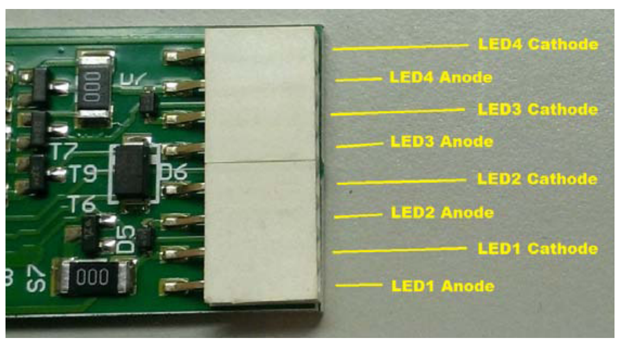

Figure 12. Off-board Connections, from Driver Board to LEDs

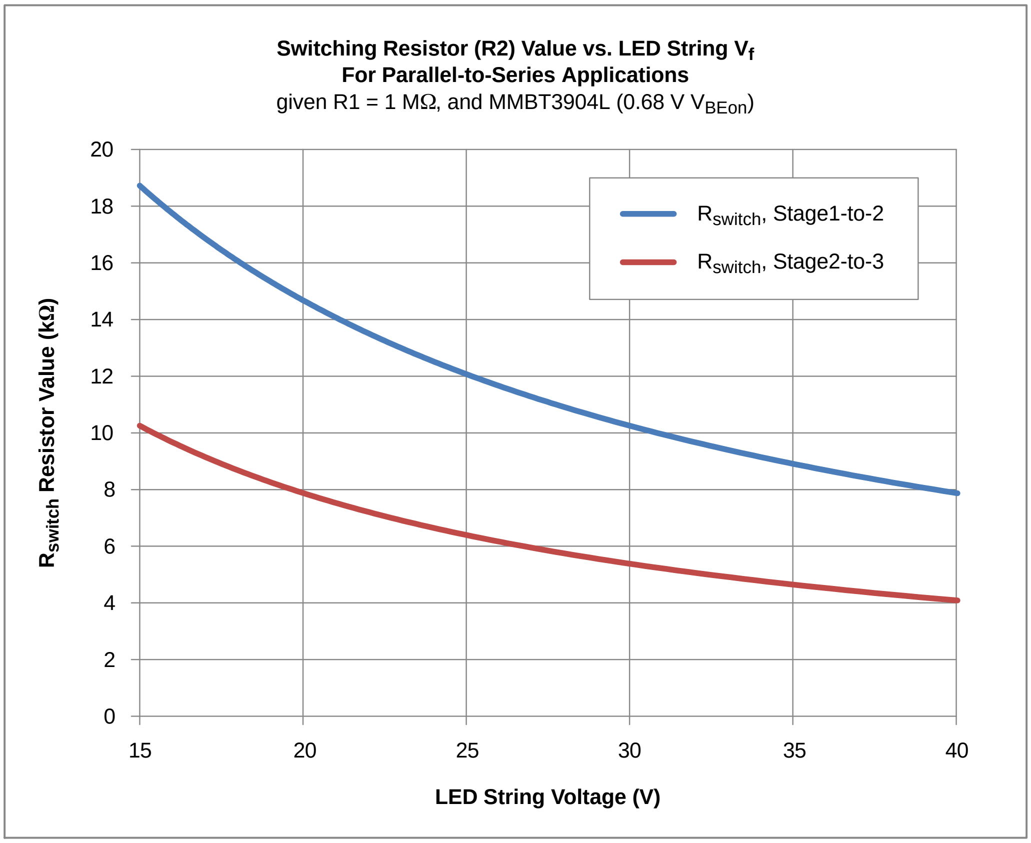

Figure 13. Plot showing recommended values for the R_{switch} resistor values to determine the driver's switchpoints. The second-to-third stage trigger resistor is roughly half the value of the first-to-second stage trigger resistor

Bill of Materials

Table 6. BILL OF MATERIALS FOR CIRCUIT SHOWN IN FIGURE 1

Designator	Qty	Description	Value	Tolerance	Manufacturer	Part Number
CCR1	1	Constant Current Regulator	120 V, 30 mA	±15%	ON Semiconductor	NSIC2030JB
CCR2	1	Constant Current Regulator	120 V, 50 mA	±15%	ON Semiconductor	NSIC2050JB
F1	1	Fuse	250 V, 1 A	−	Any	−
MOV1	1	Varistor	150 V_{AC}	−	Any	−
D1−D4	4	Diode	400 V, 1 A	−	ON Semiconductor	MRA4004
D5, D7	2	Diode	75 V, 200 mA	−	ON Semiconductor	BAS16H
D6	1	Diode	250 V, 200 mA	−	ON Semiconductor	BAS21L
C1	1	Capacitor	2.2 nF, 500 V	−	Any	−
C2−C3	2	Capacitor	1 nF, 10 V	−	Any	−
Q1, Q11	2	NPN Transistor	40 V, 200 mA	−	ON Semiconductor	MMBT3904L
Q2, Q10	2	NPN Transistor	350 V, 100 mA	−	ON Semiconductor	MMBT6517L
Q3, Q5, Q8	3	NPN Transistor	140 V, 600 mA	−	ON Semiconductor	MMBT5550L
Q4, Q6, Q7, Q9	4	PNP Transistor	150 V, 500 mA	−	ON Semiconductor	MMBT5401L
R1, R15	2	Resistor	1 MΩ, 1/8 W	±1%	Any	−
R2	1	Resistor	9.53 kΩ, 1/8 W	±1%	Any	−
R3, R14	2	Resistor	300 kΩ, 1/8 W	±1%	Any	−
R4	1	Resistor	30 kΩ, 1/8 W	±1%	Any	−
R5, R9	2	Resistor	1 kΩ, 1/8 W	±1%	Any	−
R6	1	Resistor	255 Ω, 1/8 W	±1%	Any	−
R7−R8	2	Resistor	24.9 kΩ, 1/8 W	±1%	Any	−
R10, R13	2	Resistor	2.2 kΩ, 1/8 W	±1%	Any	−
R11−R12	2	Resistor	15 kΩ, 1/8 W	±1%	Any	−
R16	1	Resistor	4.7 kΩ, 1/8 W	±1%	Any	−
LED1−LED4	4	LEDs	36 V, 480 mA	−	Any	−

Further Reference

For a similar design (3-stage, Parallel-to-Series) adapted to 230 V_{AC}, please refer to design note DN05047.

- Design Note – DN05047/D: 230 V_{AC}, Low-Cost, Dimmable, 3-stage, LED Lamp Circuit

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