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## Design Note – DN05063/D

# 2-Stage Parallel-to-Series, ENERGY STAR® Low-Cost Linear LED Driver Design (120$V_{AC}$)

| Device | Application | Topology | Efficiency | Input Power | Power Factor | THD | Lumens | Driver Efficacy |
|---|---|---|---|---|---|---|---|---|
| NSIC2020JB, NSI50010Y | AC LED Driver | Linear | 84% | 2.8 W | 0.99 | 16% | 265 lm | 94 lm/W |

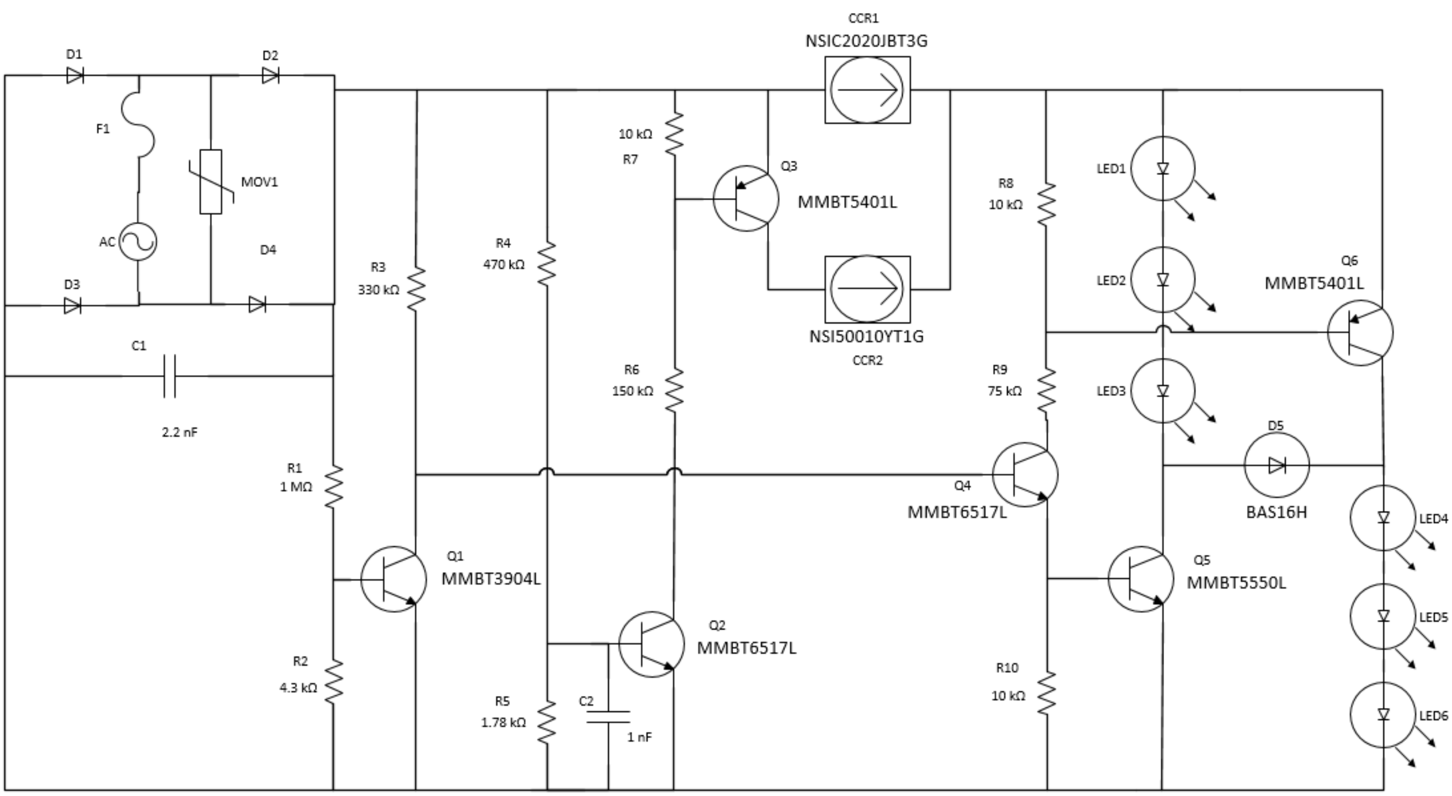


Figure 1 – Two-Stage Parallel-to-Series LED Driver Circuit

## Overview

This LED driver design uses innovative techniques to provide a cost-efficient and effective AC LED lighting solution for 120 $V_{AC}$ mains power. Its primary features are high efficiency, high power factor, low THD, dimming capability, scalable nature, and ENERGY STAR® compliant efficacy.

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

The driver uses a parallel-to-series topology that dynamically adjusts the total LED forward voltage ($V_f$) to match the bridge output voltage. This practice helps the circuit obtain its high efficiency.

The circuit uses 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 boost current at high voltages to improve PF and THD.

## Circuit Description

The circuit consists of a full-wave bridge rectifier (D1 – D4), parallel-to-series switching circuitry (R1 – R3, R8 – R10, C1, Q1, Q4 – Q6, D5), CCR turn-on circuitry (R4 – R7, C2, Q2 – Q3), CCRs (CCR1 – CCR2), and LEDs (LED1 – LED6).

## Circuit Operation

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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 two configurations with varying bridge output voltage.

The first LED configuration, when the bridge output is between 0 V and 158 V[†], is a "parallel" stage, when both strings of LEDs (LED1 – LED3 forms one string, LED4 – LED6 forms another) are in parallel with each other. CCR1 is on, and the Q4, Q5, and Q6 transistors are all on. The D5 diode is reverse-biased. Transistors Q1 and Q2 are off, which are working as voltage threshold detectors. CCR current (when above the LED string $V_f$ of 72 V) is split down both strings of parallel LEDs.

The second LED configuration, when the bridge output is above 158 V, shifts the LEDs into one series string (LED1 through LED6 are all in series). Q1 initiates the transition into the second stage switching on at 72 V due to the R1/R2 voltage divider. When Q1 turns on, Q4's $V_{BE}$ is shorted, eliminating base current for transistors Q5 and Q6. As these transistors turn off, the D5 diode is forward biased, connecting the LED3 cathode to the LED4 anode, such that all LEDs are in one series string. This "parallel-to-series" switching action provides the namesake of the driver.

Simultaneously with the LED's parallel-to-series switch, transistor Q2 is set to turn on using another threshold detector, triggering at about 159 V[††]. When Q2 turns on, it provides base current to the Q3 transistor, which turns on, allowing CCR2 provide additional current to the LEDs. Happening only at high voltages, this arrangement allow the the total input current waveform to match 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 voltage.

[†] 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 Semi 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 Equation 1 below:

$$(Eq.1)\quad V_{SWITCH(Q1)} = V_{BE(sat)} \cdot \frac{R1 + R2}{R2}$$

Using the values R1 = 1 MΩ, R2 = 4.3 kΩ, $V_{SWITCH(Q1)}$ = 158 V.

[††] Similar to the $V_{SWITCH(Q1)}$ relationship, Q2 is triggered on by the R4/R5 resistor divider. Also an ON Semi MMBT6517L, the expected $V_{BE(sat)}$ of Q2 is roughly 0.60 V, and by Equation 2 below:

$$(Eq.2)\quad V_{SWITCH(Q2)} = V_{BE(sat)} \cdot \frac{R4 + R5}{R5}$$

Using the values R4 = 470 kΩ, and R5 = 1.78 kΩ, $V_{SWITCH(Q11)}$ = 159 V.

## Design Considerations (1)

Special design modifications for this circuit include LED string forward voltage ($V_f$) and CCR1 current value. For optimal performance, it is recommended that LED strings of $V_f$ between 30 V and 80 V are used. Generally, the higher the LED $V_f$, the greater the efficiency, though the benefits of PF/THD-improving CCR1 are diminished. 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 R5 to be changed to properly adjust the switching points. The graph of Fig. 14 shows roughly the relationship of these switching resistors versus LED forward voltage.

For higher power circuits, multiple/increased value CCRs may be used in parallel with CCR1 with no adverse effects. Increased value/multiple CCRs may be used in place of CCR2 with proper adjustments to the R6 resistor.

For higher power designs, R9 should be reduced so as to increase the amount of base current available to Q5 and Q6. This allows Q5 and Q6 to pass more LED current during the parallel stage.

# Circuit Data

| Attribute | 110 $V_{AC}$ | 120 $V_{AC}$ | 130 $V_{AC}$ |
|---|---|---|---|
| $I_{RMS(IN)}$ (mA) | 21.12 | 23.89 | 25.32 |
| PF | 0.982 | 0.987 | 0.989 |
| THD ($I_{RMS}$, %) | 19.02 | 16.27 | 14.29 |
| $P_{IN}$ (W) | 2.29 | 2.83 | 3.27 |
| Efficiency (%) | 76.7 | 84.3 | 83.0 |
| Lumens (lm) | - | 265 | - |
| Driver Efficacy (lm/W) | - | 93.6 | - |
| Dimming? | Yes | Yes | Yes |

Table 1 **–** Electrical characteristics for the circuit shown in Fig. 1.

# Key Features

- Functional with wide range of standard phase-cut TRIAC dimmers (CFL/LED dimmers recommended).
- Low-cost bill of materials.
- Light output comparable to 24W incandescent.
- High driver efficacy for luminaire Energy Star compliance.
- PF > 0.98.
- Efficiency > 80% over voltage range.
- THD < 20%.
- No EMI filter needed.
- Tunable for various LED voltages (suggested 30 – 80 V strings).
- Scalable to various currents/power levels.

# Dimmer Compatibility

| Manufacturer | Serial Number |
|---|---|
| Lutron | Skylark CTCL-153PD |
| Lutron | Credenza TTCL-100L |
| Leviton | Sureslide 6615P |
| Pass & Seymour | Legrand 450 DCL453-PTCG |

Table 2 – The circuit was fully functional with each dimmer listed above.

# Bill of Materials

| Designator | Manufacturer | Part No. | Qty | Description | Value | Tolerance |
|---|---|---|---|---|---|---|
| CCR1 | ON Semi | NSIC2020JB | 1 | Constant Current Regulator | 120 V, 20 mA | ±15% |
| CCR2 | ON Semi | NSI50010Y | 1 | Constant Current Regulator | 50 V, 10 mA | ±15% |
| F1 | Any | - | 1 | Fuse | 250 V, 1 A | - |
| MOV1 | Any | - | 1 | Varistor | 150 $V_{AC}$ | - |
| D1 – D4 | ON Semi | BAS21SL | 2 | Dual Diode, Series | 400 V, 1 A | - |
| D5 | ON Semi | BAS16H | 1 | Diode | 75 V, 200 mA | - |
| C1 | Any | - | 1 | Capacitor | 2.2 nF, 500 V | - |
| C2 | Any | - | 1 | Capacitor | 1 nF, 10V | - |
| Q1 | ON Semi | MMBT3904L | 1 | NPN Transistor | 40 V, 200 mA | - |
| Q2, Q4 | ON Semi | MMBT6517L | 2 | NPN Transistor | 350 V, 100 mA | - |
| Q3, Q6 | ON Semi | MMBT5401L | 2 | PNP Transistor | 150 V, 500 mA | - |
| Q5 | ON Semi | MMBT5550L | 1 | NPN Transistor | 140 V, 600 mA | - |
| R1 | Any | - | 1 | Resistor | 1 MΩ, 1/8 W | ±1% |
| R2 | Any | - | 1 | Resistor | 4.3 kΩ, 1/8 W | ±1% |
| R3 | Any | - | 1 | Resistor | 330 kΩ, 1/8 W | ±1% |
| R4 | Any | - | 1 | Resistor | 470 kΩ, 1/8 W | ±1% |
| R5 | Any | - | 1 | Resistor | 1.78 kΩ, 1/8 W | ±1% |
| R6 | Any | - | 1 | Resistor | 150 kΩ, 1/8 W | ±1% |
| R7, R8, R10 | Any | - | 3 | Resistor | 10 kΩ, 1/8 W | ±1% |
| R9 | Any | - | 2 | Resistor | 75 kΩ, 1/8 W | ±1% |
| LED1 – LED6 | Any | - | 6 | LEDs | 48 V, 30 mA | - |

Table 3 – Bill of Materials for the circuit shown in Figure 1.

## Representational Circuit Diagrams

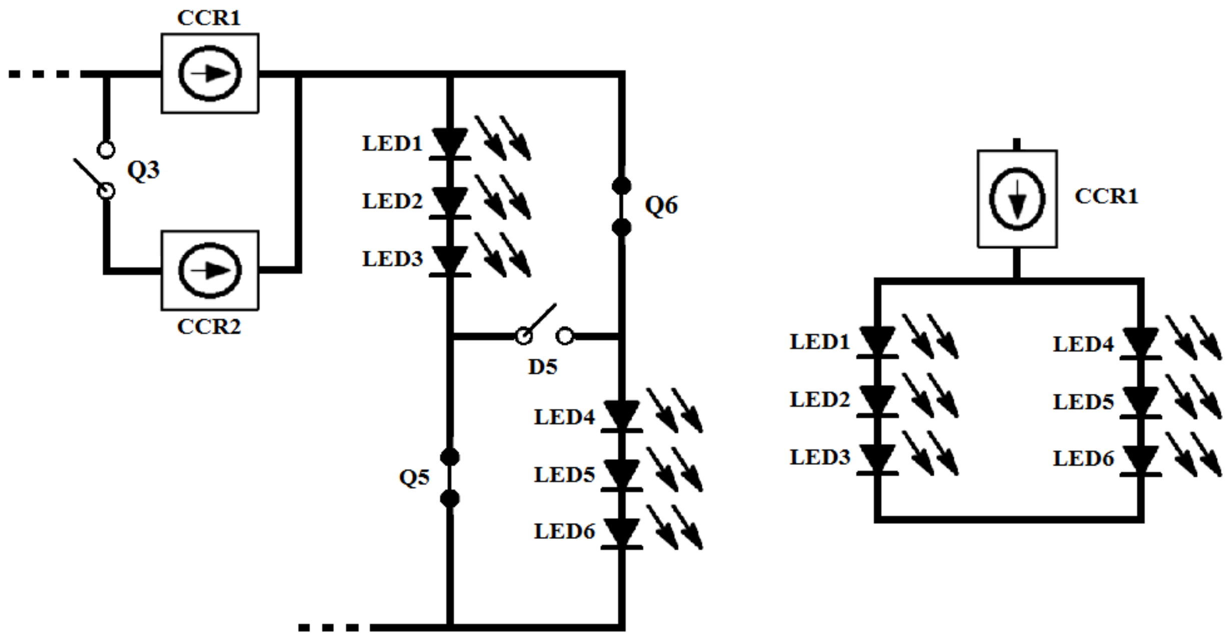


Figure 2 – Stage 1/Parallel configuration of LEDs, showing behavior of switching circuitry. Transistors Q5 and Q6 are on, which reverse biases D5. The LEDs are then in parallel below the CCR. The driver is in this state at bridge voltages below 158 V.

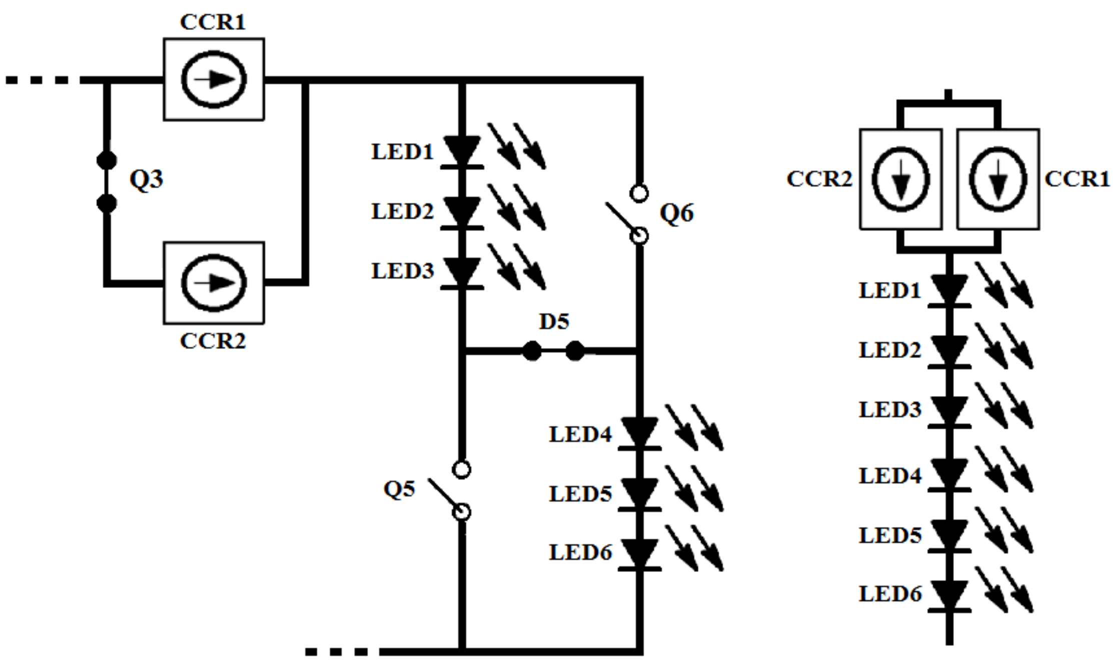


Figure 3 – Stage 2/Series configuration of LEDs. Transistors Q5 and Q6 are now open, and the D5 routing diode connects the two LED strings. The driver is in this state above 158 V.

# Waveforms

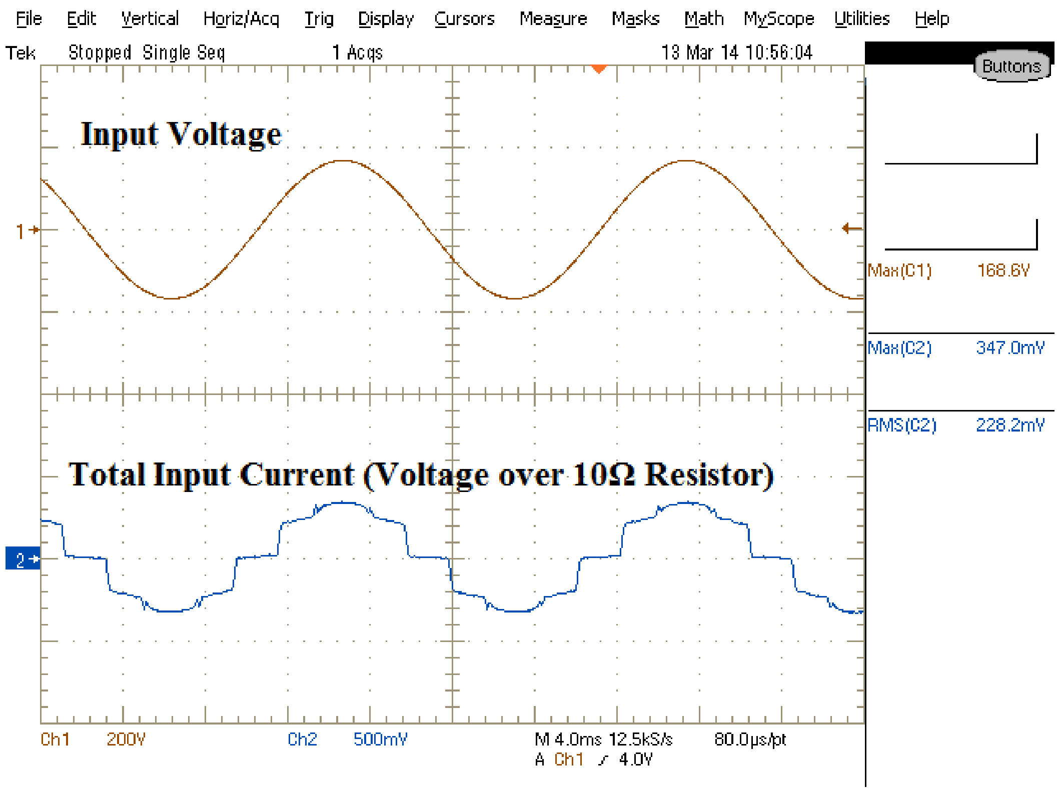


Figure 5 – The total input current follows the voltage waveform very closely, yielding outstanding power factor and THD performance.

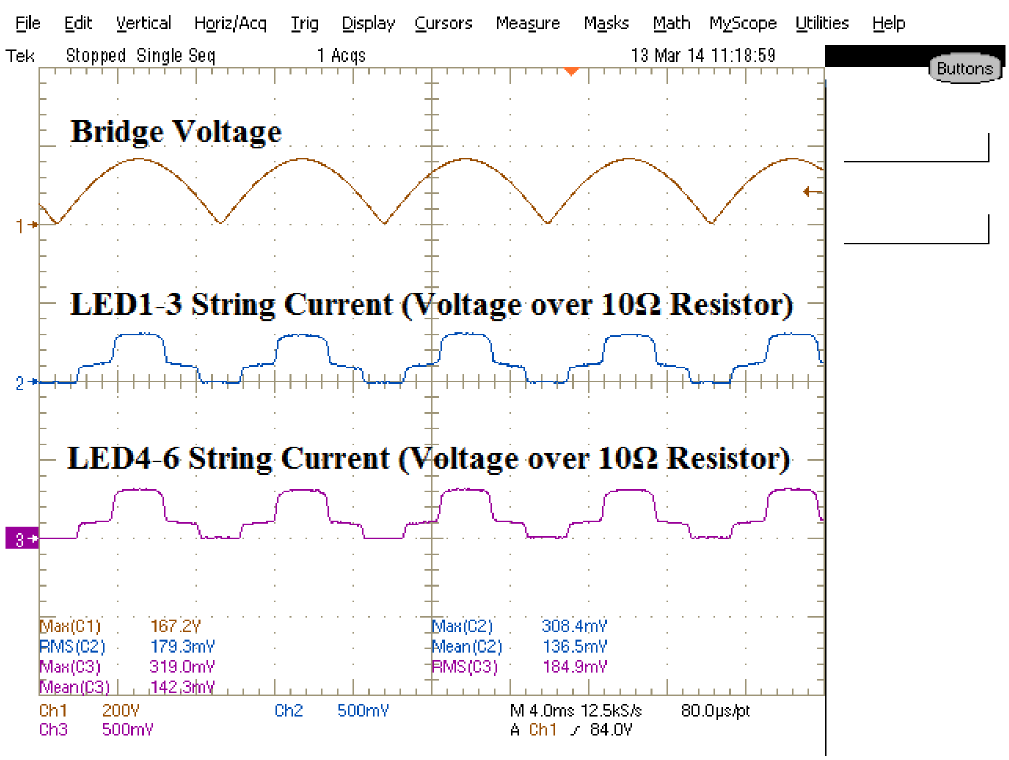


Figure 6 – LED current through each of the LED strings. Note the current waveforms are nearly identical, as well as the two distinct levels of current, coinciding with the two LED configurations.

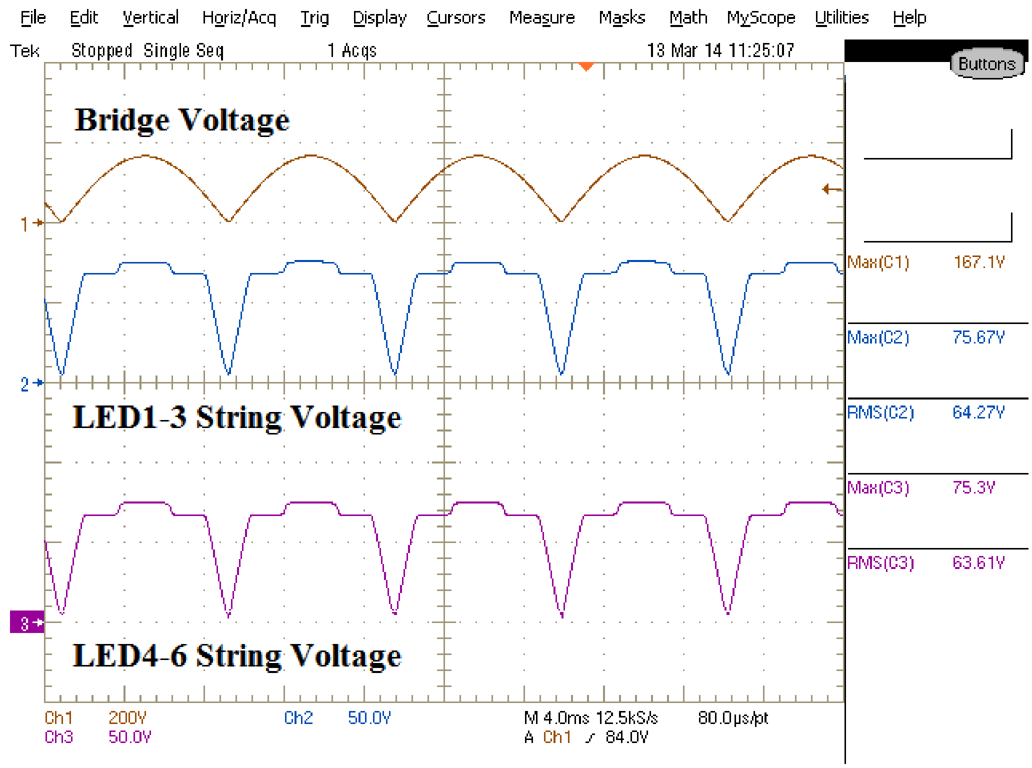


Figure 7 – The LED forward voltage is identical at all times for all LEDs. When the LED voltage is not 0 V, the LEDs are on. Given an LED $V_f$ of 72 V, the LEDs are on about 72% of the time. The two voltage levels coincide with the parallel/series stages of the driver—as current increases through the LEDs, the voltage increases slightly as well due to series resistance.

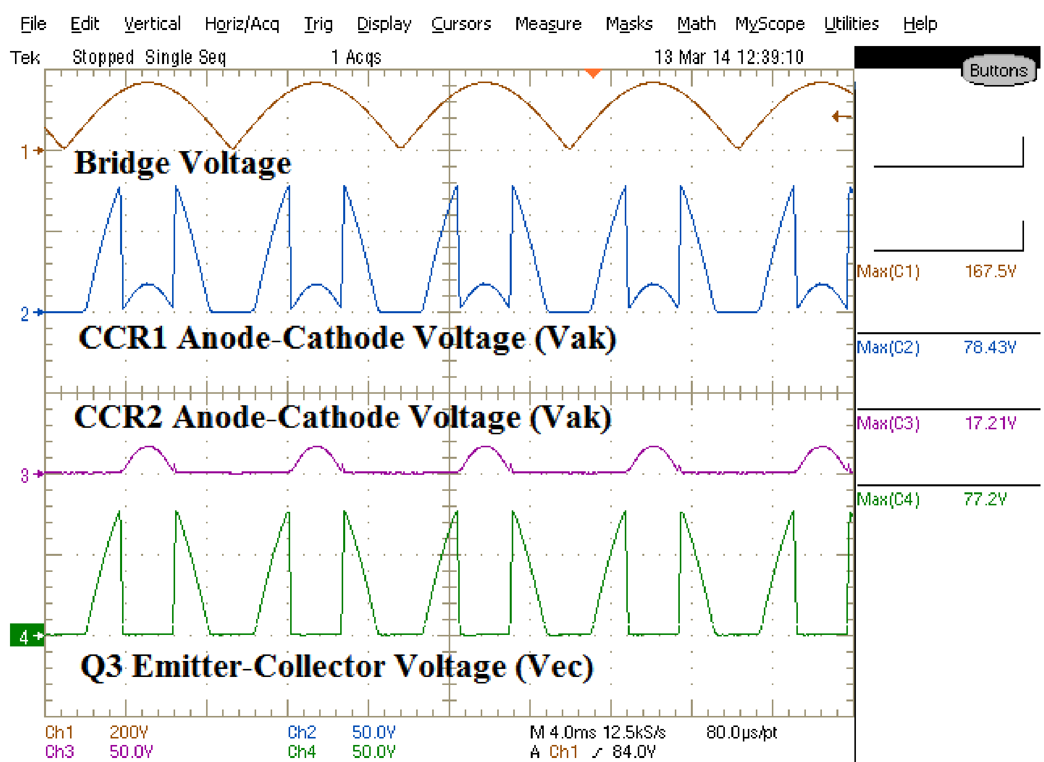


Figure 8 – The CCR1 $V_{ak}$ demonstrates the different stages of the LED configurations. Q3 blocks CCR3 from conducting only until the highest bridge voltages. Q3 and CCR2 are in parallel with CCR1, thus the sum of Q3 and CC2 voltages always equal CCR1.

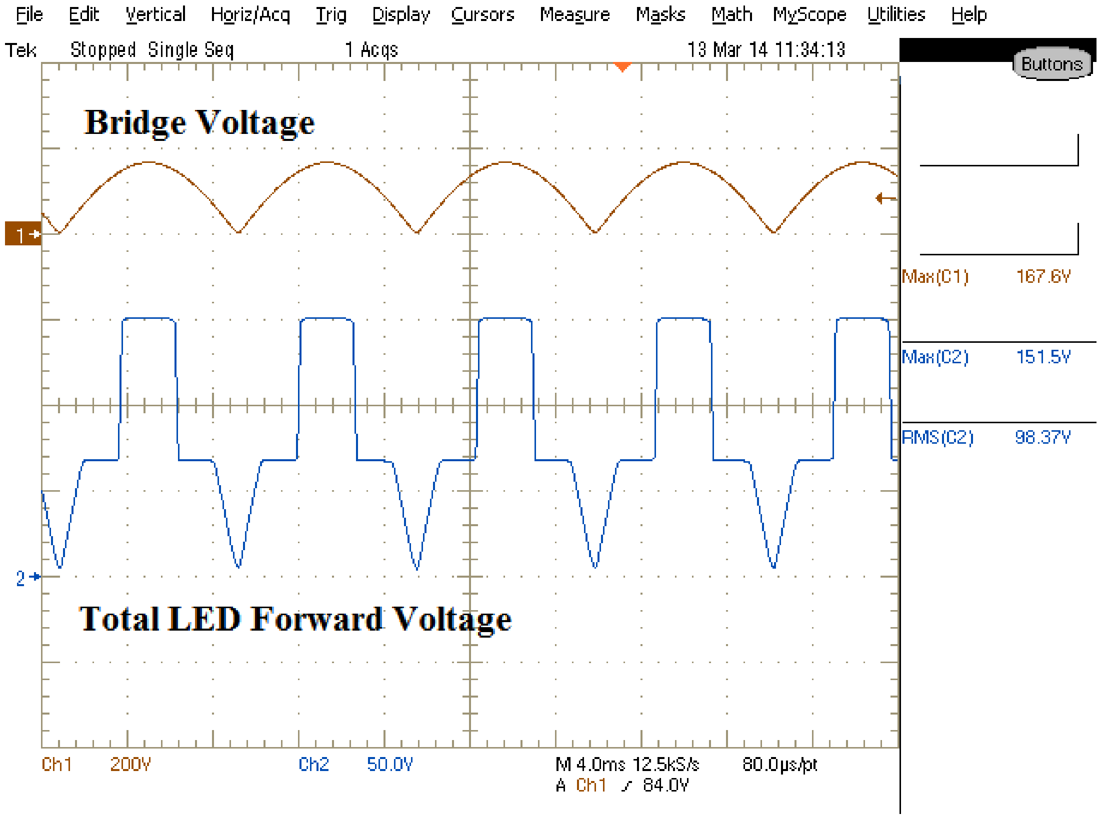


Figure 9 – This capture shows the "total" LED voltage, seen from the CCR cathode to rectified ground. The two levels indicate the LED configurations—the high level is the series mode, and the lower level is the parallel mode.

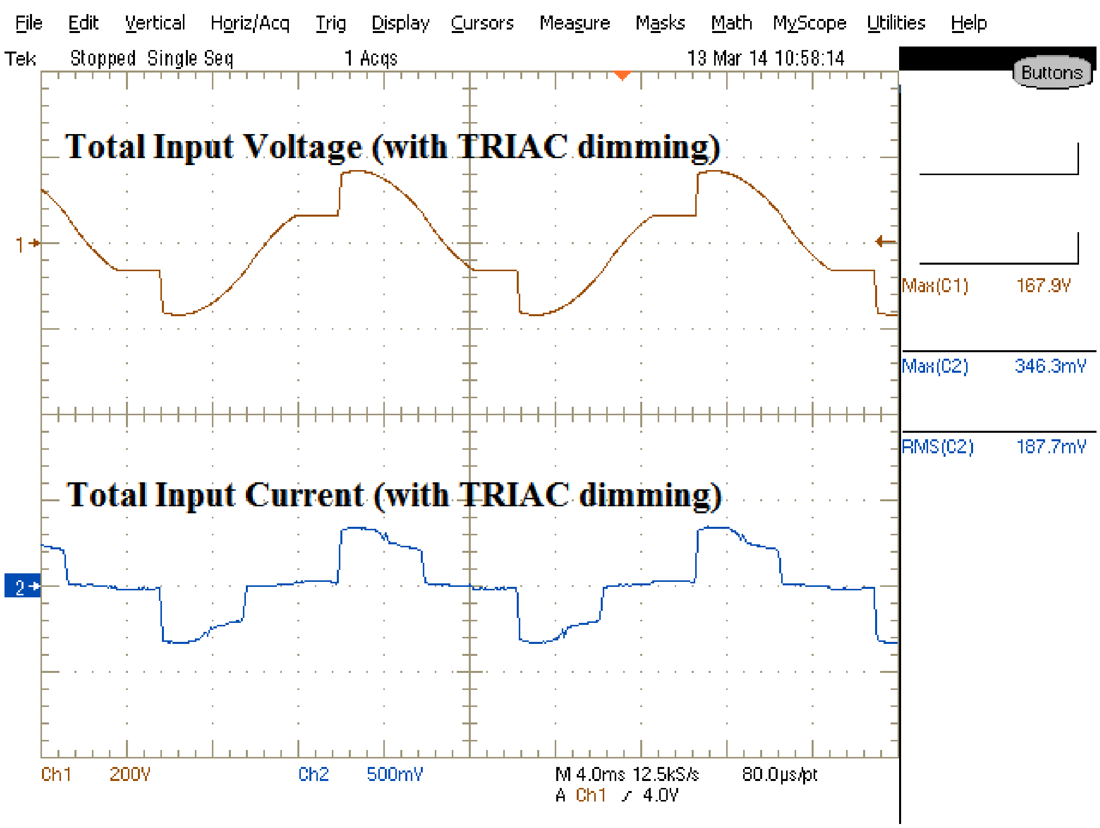


Figure 10 – The circuit receives no input current when the TRIAC is off, and the current is normal when the TRIAC is on.

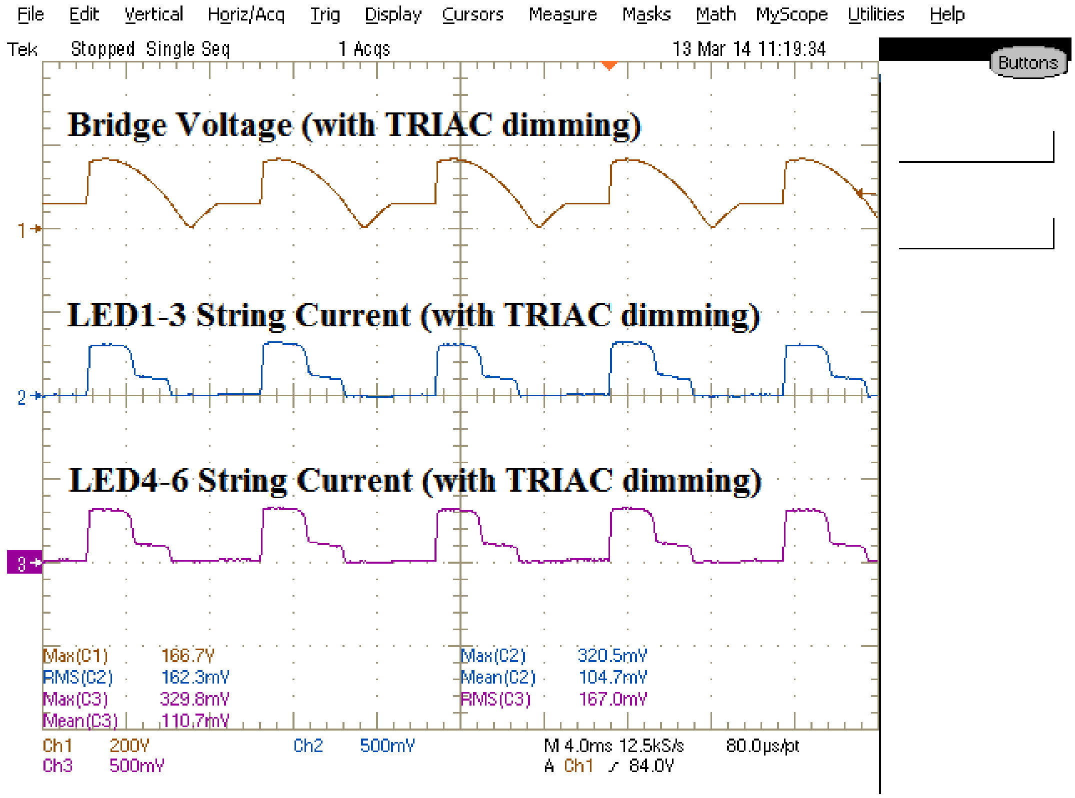


Figure 11 – LED current waveforms are unaffected when the TRIAC is on, and the LEDs shut off perfectly when the TRIAC is off.

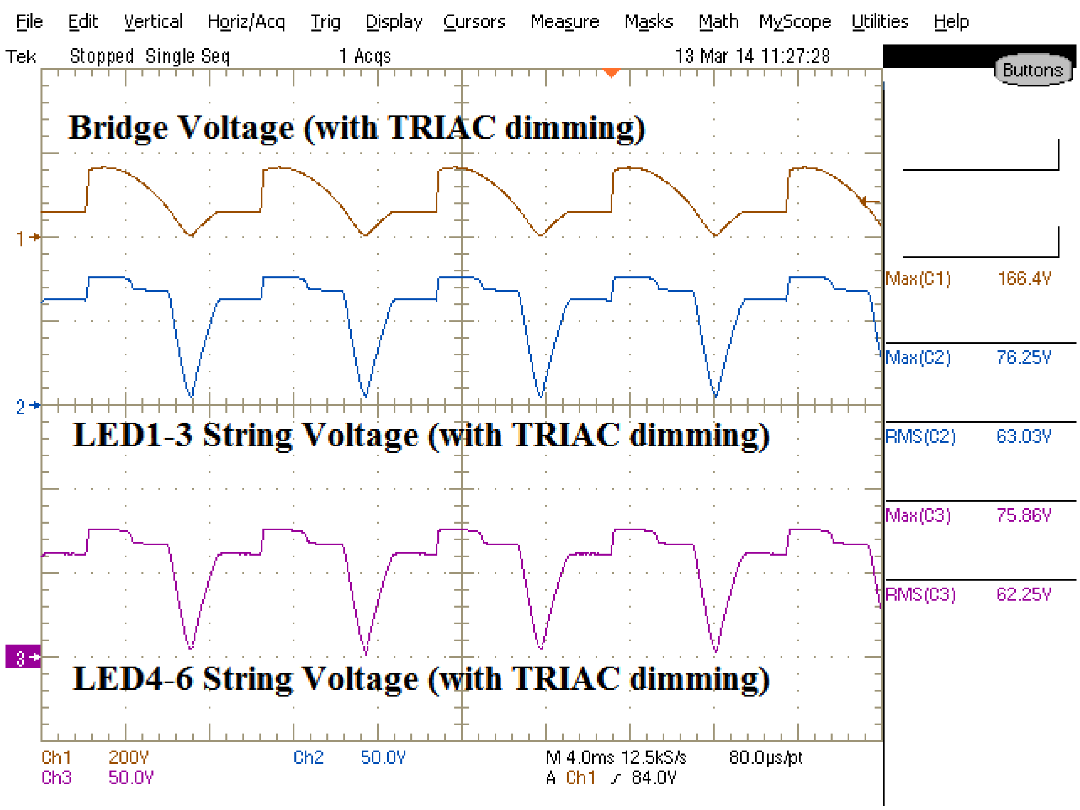


Figure 12 – LED1's voltage and current waveforms, unaffected by TRIAC dimming. The voltage on the LEDs is due to the non-zero dimmer output voltage during the "fully dim" state. This behavior is common for dimmers that include on-off/preset switches.

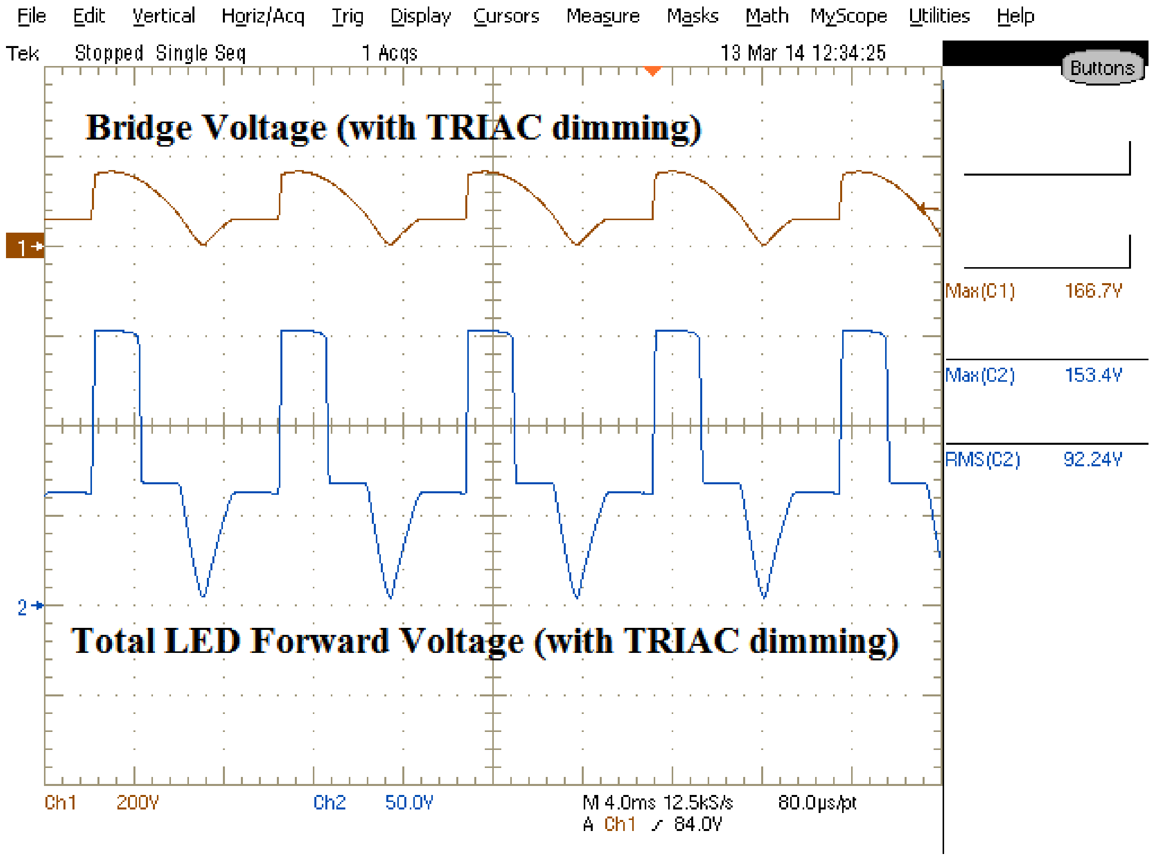


Figure 13 – This capture shows the total LED voltage, showing the configuration of the LED strings during TRIAC dimming. The driver continues to function and switch normally even in the presence of a dimmer.

# Design Considerations (2)

As a linear driver without voltage transformation capabilities, the LEDs themselves play an important role in determining the electrical performance characteristics of the driver. Efficiency, power factor, total harmonic distortion, and dimmability are all, to some degree, functions of the LED voltages with relation to the bridge voltage.

As such, the voltage thresholds and switchpoints that govern parallel-to-series operation must be adjusted correspondingly must be changed with LED string voltages. To maximize efficiency and maintain constant LED current, it is recommended to keep about 6 V on the CCR after a parallel-to-series switch (see Fig. 8, the minimum points on CCR1 $V_{AK}$ are roughly 6 V). The graph below offers a mathematical characteristic for the recommended switching resistor (in this design, R2) to optimize efficiency for a given LED string voltage.

Figure 14 below does not take into account series resistance of the LEDs, where the LED forward voltage increases due to the increase in LED current when switching to series mode (see levels in LED string voltage in Fig. 7, for example). This varies across LEDs greatly, which low-to-mid power LEDs being the most susceptible. The plot of Fig. 14 below is provided as a general ballpark to expedite the design process. In practice, small adjustments may need to be made at the judgment of the designer.

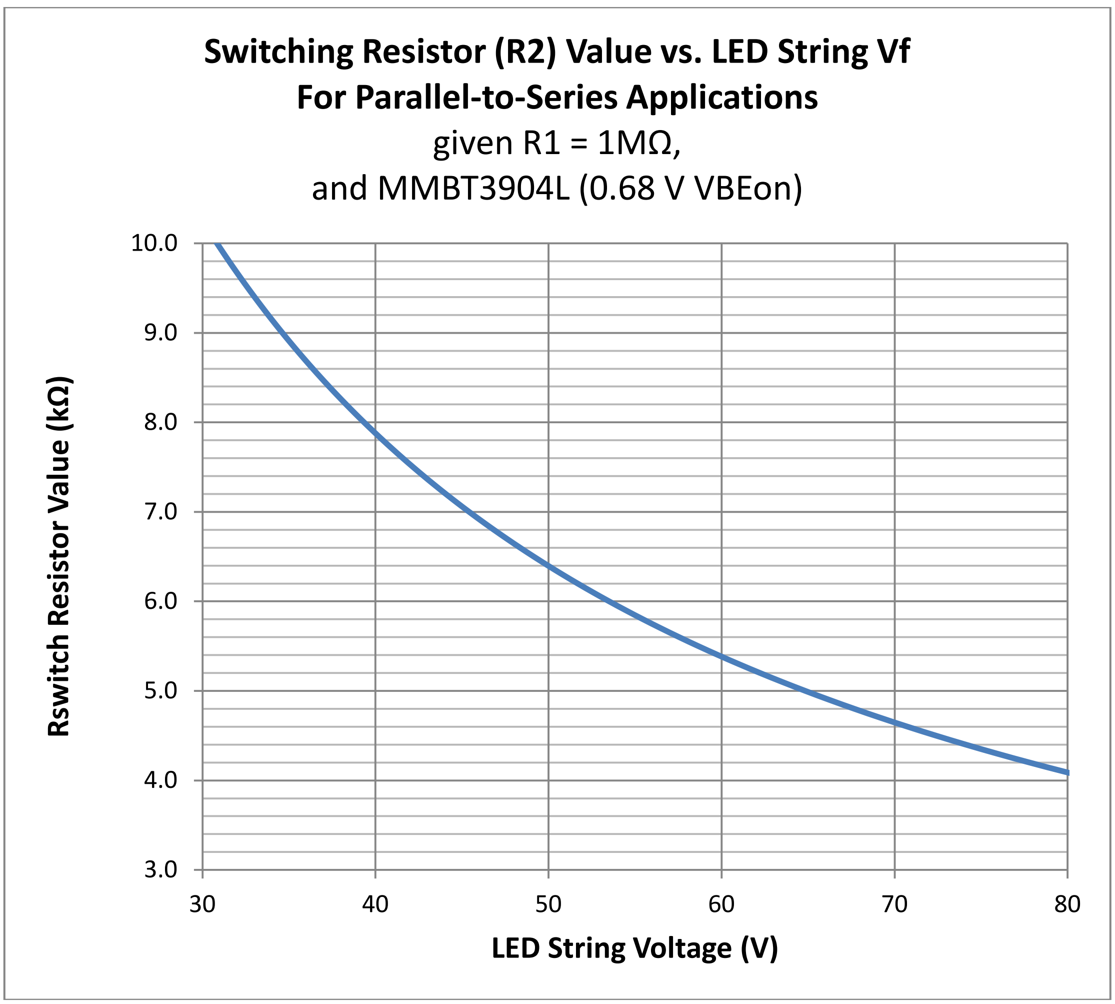


Figure 14 – This graph shows the required R2 resistor value for optimal switching of the LEDs. These values are derived from Equation 1, to serve as a general ballpark for designing with different LEDs.

## Sample Layout

An example of a sample layout is shown below. Gerber files are attached to the NSI50010YT1G and NSIC2020JBT3G part numbers and may be obtained at either of the following links:

**NSIC2020JB Design Note Catalog:**
http://www.onsemi.com/PowerSolutions/supportDoc.do?type=Design Notes&rpn=NSIC2020JB

**NSI50010Y Design Note Catalog:**
http://www.onsemi.com/PowerSolutions/supportDoc.do?type=Design Notes&rpn=NSI50010YT1G

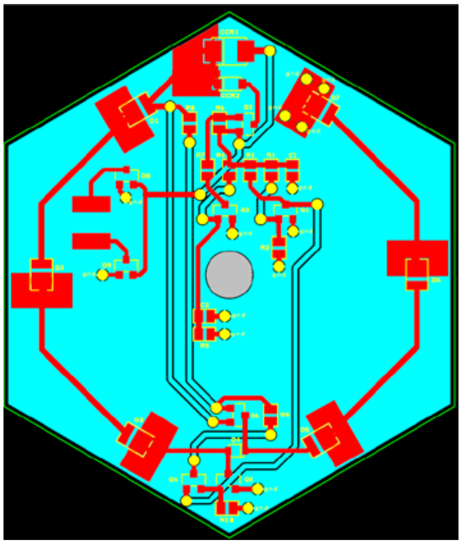

Figure 15 – PCB for ceiling-mount fixture available online.

## Further Reference

For similar designs (2-Stage, Parallel-to-Series), please refer to these other design notes:

- **Design Note – DN05046/D: 120V$_{AC}$, Low-Cost, Dimmable, Linear, Parallel-to-Series LED Driving Circuit**

  http://www.onsemi.com/pub_link/Collateral/DN05046-D.PDF

- **Design Note – DN05052/D: 120V$_{AC}$ Low-Cost, Dimmable, Linear, Parallel-to-Series with Switch-In CCR LED Lighting Circuit**

  http://www.onsemi.com/pub_link/Collateral/DN05052-D.PDF



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