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Design Note – DN05079/D

Direct-AC, Linear LED Driver Topology: CCR Straight Circuit (120 V_{AC} & 230 V_{AC})

Device	Application	Topology	Efficiency	Input Power	Power Factor	THD
NSIC20x0JB	AC LED Lighting	Direct AC, Linear	68 – 84 % Variable	6 – 14 W	0.92 – 0.97	20 – 39%, Variable

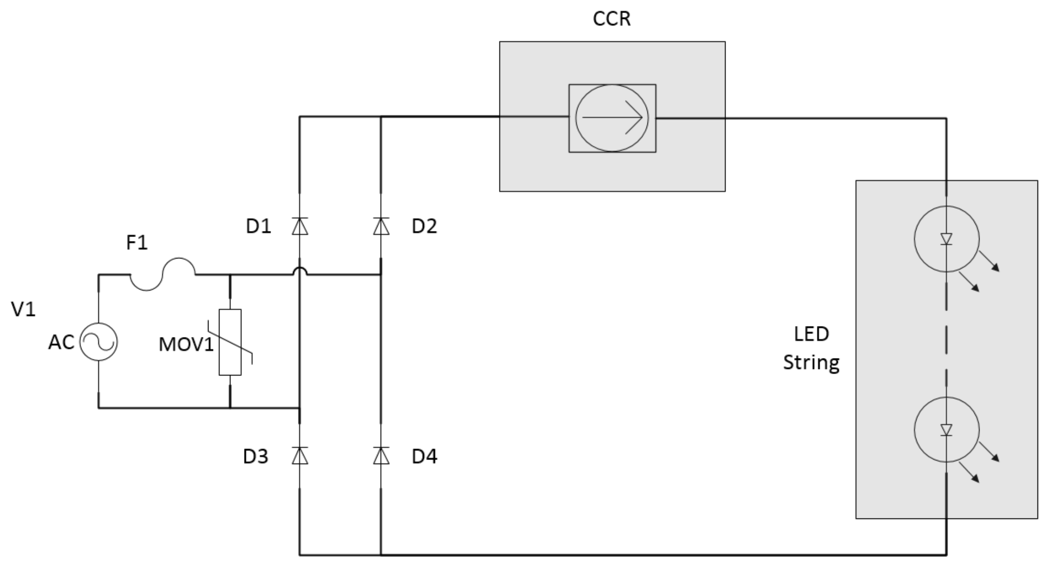

Figure 1 – General "Straight Circuit" CCR-based LED Driver Schematic

Overview

This document presents a simple, low-cost LED driver topology useful for AC LED lighting solutions at any mains voltage or frequency. This cost-effective driver design combines good power factor, simplicity, high efficiency, and impressive driver scalability in a very adaptive and versatile platform solution.

The circuit is designed for use within a wide input voltage range, and can be made to operate anywhere between 90 V_{AC} and 300 V_{AC}. The driver works best when optimized for a specific supply voltage range (such as 100 – 130 V_{AC} or 190 – 250 V_{AC}), which may influence LED load design.

The circuit employs ON Semiconductor Constant Current Regulators (CCRs) to regulate LED current and protect LEDs from over-voltage conditions. This driver is extremely scalable, and can support many modular extensions for circuit tuning and performance, which will be referred to and supported by this note.

The driver traditionally drives a single LED load, which may be composed of multi-junction high-voltage (HV) LEDs or multiple standard low-voltage LEDs. The "LED String" may flexibly represent a high-voltage string of multiple LEDs, or a single COB LED. The LED load will need to be appropriately designed for CCR over-voltage considerations, and this note will discuss conditions and refer to protection techniques.

The circuit is protected from mains transients by a fuse and metal-oxide varistor. The driver can also accommodate EMI filtering techniques.

This technical note will first overview general behaviors of the circuit, identify design-dependent performance parameters, and then finish off with a closer examination of six specific designs.

Key Features

- Wide input voltage range.
- High-voltage transient and tolerance protection.
- Simple, low-cost implementation.
- Simple and flexible load design, highly compatible with COB implementations.
- High power factor across voltage range.
- Modular design flexibility, can accommodate many functions (EMI filter, OVP, etc.)
- Compatible with most phase-cut dimmers.
- Adjustable for different LED voltages.
- Scalable for different currents/power levels.
- Predictable electrical performance

Circuit Description

The circuit consists of, at a minimum, a full-wave bridge rectifier (D1 – D4), a current regulator (“CCR”), and an LED load (represented by “LED String”) connected in series, as shown in Figure 1. Other more specific schematics are shown later on in Figures 3, 11-16.

For high-voltage (220 V_{AC} and above) or low load voltage (see Fig. 10) an OVP block is recommended, which as described by Figure 2 and shown in Figure 3b, consists of a threshold detector (R1 – R2, Q1), pass transistor network (Q2, R3), and power resistor (R4).

Circuit Operation and Design

The bridge rectifier outputs a half-wave sine peaking at about 170 V for 120 V_{AC}, and about 320 V for 230 V_{AC}. This bridge output is referenced between the cathodes of D2 and D4 to the anodes of D1 and D3.

The circuit drives the LED load directly off of the output of the bridge voltage, hence the name “direct-AC.” The driver’s design philosophy is to achieve maximum simplicity with minimum component count. For a more streamlined approach, this note will only overview OVP schemes in particular cases.

The driver’s operation is very simple to understand. As a linear driver, the CCR requires a voltage drop to perform regulation (typ. 1.8 V minimum), and for the LEDs to turn on, there must be sufficient voltage provided by the bridge. Therefore, the combination of these two conditions means that light will only be produced when the bridge voltage is above the LEDs and minimum CCR voltage combined.

$$Eq.1) \qquad Bridge \geq 1.8\, V_{AK} + LED\ V_f$$

As the LEDs will turn on with high voltage, they must turn off with low voltage. This lends the driver a “duty cycle”-like effect, determined by the magnitude of the LED load voltage. Furthermore, standard phase-cut dimming modifies the phase length of this duty cycle, emulating PWM-like behavior and avoiding the non-linear light creation of current modulation. Whether dimming or not, this duty-cycle behavior inherently increases LED lifetime and reliability.

When the LEDs are on, the remaining voltage is dropped on the CCR or current regulator, which in most cases, directly connects the bridge and LEDs, as implied in Eq. 2 below.

$$Eq.2) \qquad V_{bridge}(t) = V_{CCR}(t) + V_f$$

This is the source of most of the power lost in a straight circuit driver topology, as there will inherently be a mismatch between the varying sine-wave bridge voltage waveform and the DC-like LED load, the difference yielding power dissipation on the CCR. This effect becomes more exaggerated as the LED load voltage decreases, or the supply voltage increases. Figures 8 and 9 and Table 9 together illustrate this characteristic.

If at any time the CCR is at risk of over-voltage conditions (the maximum possible $V_{CCR,PK}$ is above the maximum voltage rating), then special OVP protection circuitry will need to be deployed to ensure reliable operation, which will be discussed in the next section.

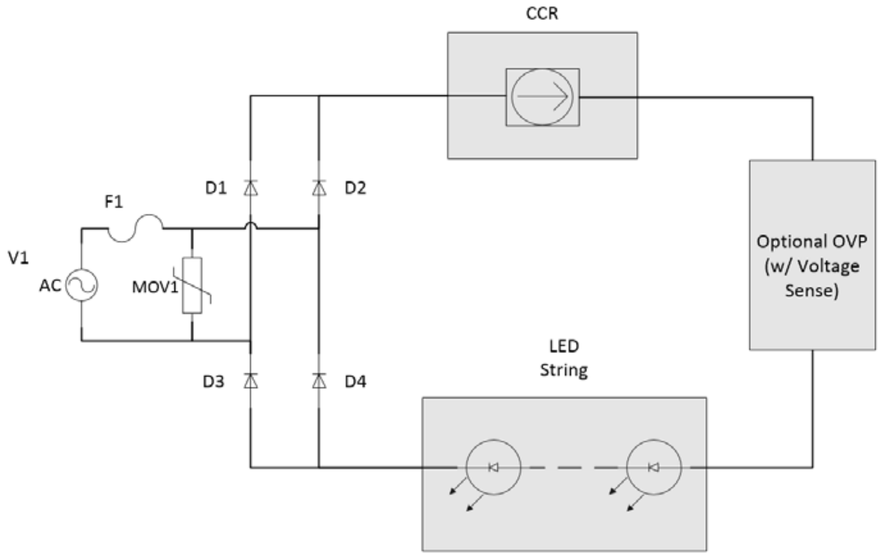

Figure 2 – General "Straight Circuit" CCR-based LED driver block diagram with OVP functionality.

With High-Voltage Protection Circuitry

If the driver is at risk of an over-voltage scenario, then additional circuitry will be necessary to monitor the CCR V_{AK} and take protective measures when necessary. The general condition for over-voltage protection necessity is given by Eq. 3.

$$Eq. 3) \quad V_{AK,max} > V_{IN,max,RMS} \cdot \sqrt{2} - V_{F,load}$$

An adequately protected circuit is shown in Figure 3b, taken from the AND9179/D application note, which overviews many other different types of over-voltage protection not covered in this technical note.

The protection circuit used in these 230 V_{AC} designs roughly measures the V_{AK} across CCR1. As a high-voltage threshold detector, Q1 controls whether current passes through a transistor (Q2), or a high-voltage power resistor (R4). When the V_{AK} threshold set by the designer is surpassed (according to Eq. 4 below), Q2 turns off, and the power resistor R4 takes on some of the voltage drop from the CCR, according to Ohm's Law. If properly designed, the R4 resistor momentarily reduces the V_{AK} on the CCR, allowing higher input voltages to be tolerated without exceeding device voltage ratings.

$$Eq. 4) \quad V_{OVP(Q1)} = V_{BE(sat)} \cdot \frac{R1 + R2}{R2}$$

Let's consider a design example protecting a 120 V, 30 mA CCR, such as the NSIC2030JBT3G. To provide sufficient margin below the device rating, let's design the OVP to activate around 100 V. When using an MMBT3904L (expected $V_{BE(sat)}$ of 0.68 V at 25 °C) as Q1 to trigger the OVP, Eq. 4 yields resistor values R1 = 1 MΩ and R2 = 6.8 kΩ to produce $V_{OVP(Q1)}$ = 101 V. This would be an appropriate protection level for a 120 V CCR.

As mentioned earlier, the power resistor R4 (as shown in Figure 3b), needs to be carefully considered so as to best protect its companion CCR network. Thankfully, only Ohm's Law must be considered: the desired voltage drop on the resistor divided by total instantaneous CCR current yields the proper resistor value, as shown in Eq. 5. Bear in mind that the desired resistor voltage drop must be less than the voltage that the OVP triggers at, so that the CCR remains in full regulation during the transition. For additional support, see Eq. 6 of application note AND9179/D.

$$Eq. 5) \quad V_{DROP,R4} = I_{CCR,max} \cdot R4$$

It follows that the Q2 device ratings are determined by the maximum instantaneous CCR current ($I_{CCR,max}$), as well as the expected voltage drop on the R4 resistor ($V_{DROP,R4}$). R3 should be selected as to provide sufficient base current for the Q2 transistor.

It should be noted that this over-voltage protection scheme does not degrade the quality or amount of light produced—it only saves the LED driver when the V_{AK} approaches unsafe levels, as determined by the designer. The output power over the LEDs is maintained when using a V_{AK}-sensitive scheme like this, although the driver's increased voltage drop means that circuit efficiency is reduced at high voltages.

Although only one design is featured in this note, many different OVP techniques and circuit schematics are reviewed further in the application notes AND9179/D and AND9203/D.

Practical implementations of the circuits represented by Figures 1 and 2 (with and without OVP) are shown here with waveforms for quick, conceptual reference, in accordance with the designators used above. All the specific designs reviewed in this design note will be one of these two templates below.

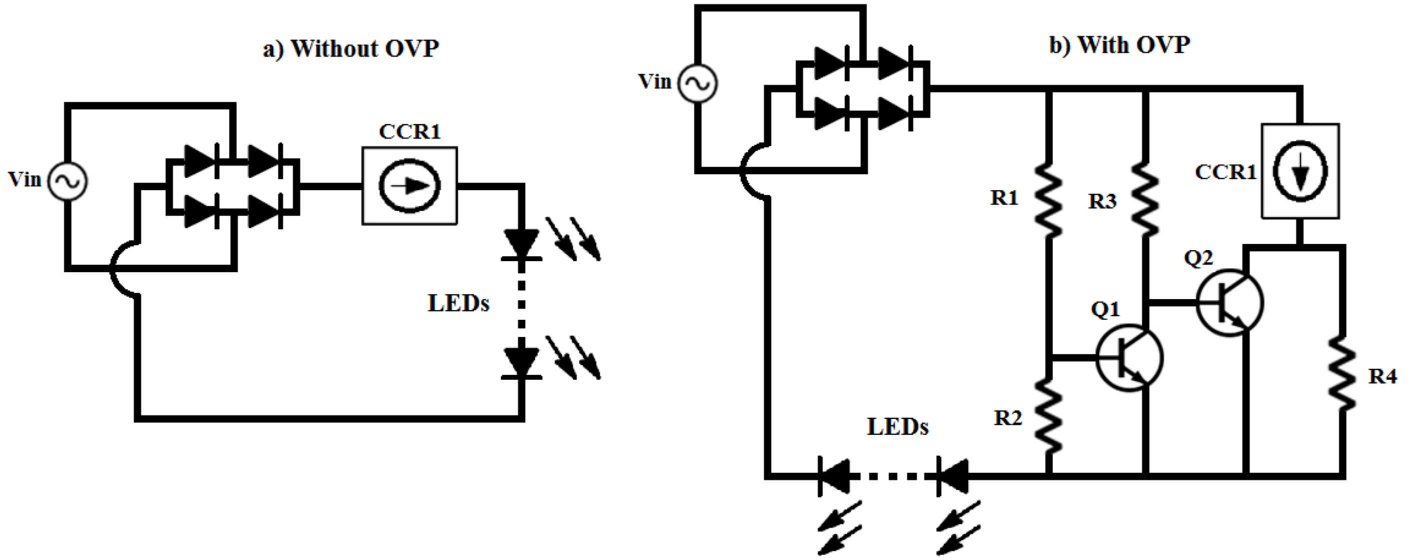

Figure 3: General straight circuit implementations for any mains voltage, shown a) without OVP, and b) with OVP.

General Waveforms

Below are screenshots demonstrating waveforms of generic straight circuit performance, with and without OVP. The first three screenshots (Fig. 4 – 6) are from a 120 V_{AC} driver utilizing a 120 V_F LED load and 50mA CCR. The fourth screenshot (Fig. 7) is a 230 V_{AC} driver utilizing a 180 V_F LED load and 20 mA CCR.

The OVP is implemented on only 230 V_{AC} designs, and not on 120 V_{AC} designs in this note, though OVP is not necessarily exclusive to high line voltages. This necessity is conditional on the relationship between the supply and load voltage levels (see Eq. 2, Fig. 10).

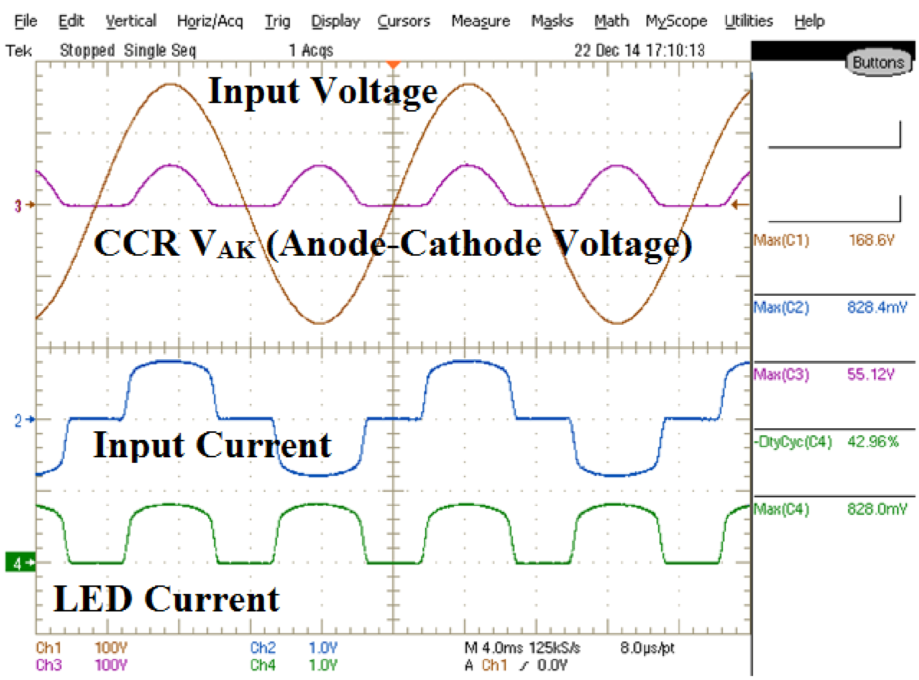

Figure 4 – The total input current follows the voltage waveform very closely, yielding high power factor and good THD performance. LED current is the supply current after rectification.

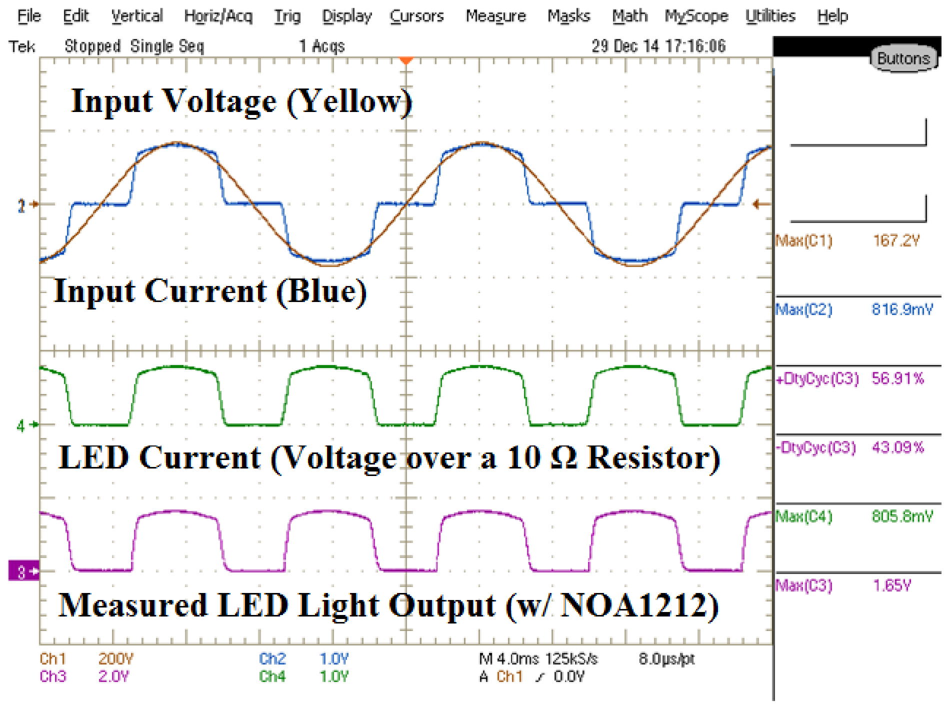

Figure 5 – A simple photodetector circuit using a NOA1212 was used to generate a waveform of the LED light output for flicker index measurements in this design note. Efficacy and light intensity vary by LED, but the general waveform shape and linear current-light relationship are maintained.

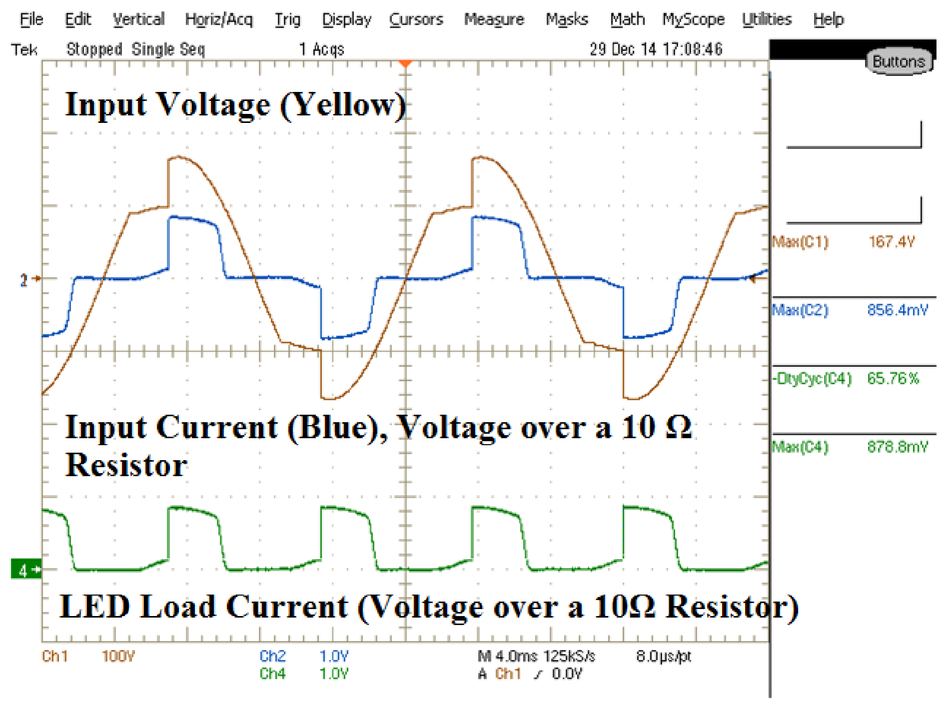

Figure 6 – Output voltage and LED current waveforms indicate no flicker when used with TRIAC dimming shown in the maximum position. This particular dimmer sports a non-zero output filter voltage during the “off” state, but the circuit receives little-to-no input current when the TRIAC is off, and the current is normal when the TRIAC is on.

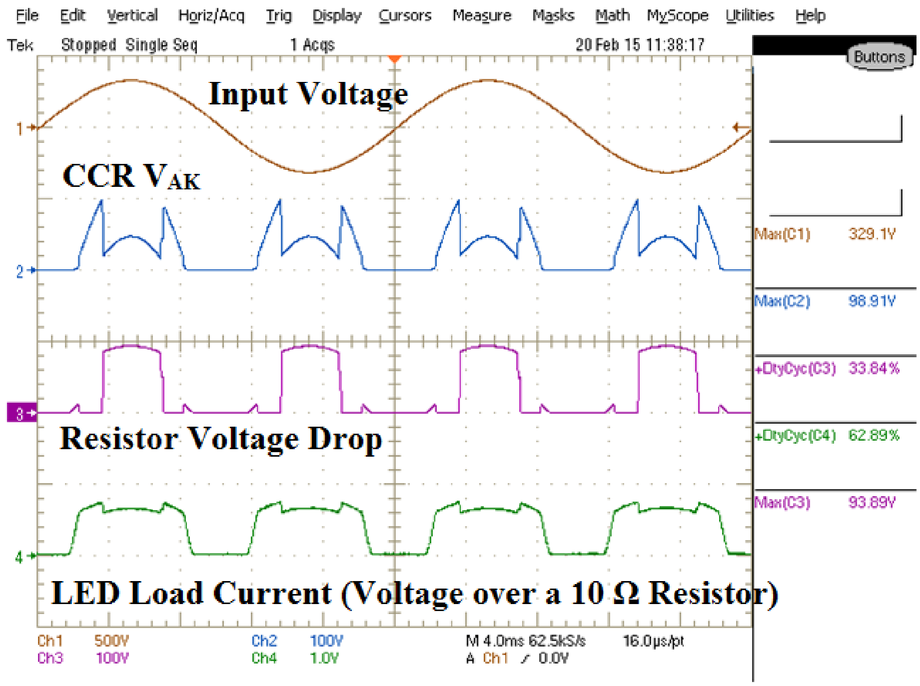

Figure 7 – With the over-voltage protection circuitry, the circuit monitors and throttles the peak voltages exercised on the CCR. In this case, we use a resistor to drop excess voltage to prevent damaging the CCR. Output current remains roughly constant while LEDs are on.

Design Dependencies and Tradeoffs

Many of the electrical and optical performance characteristics of this driver are dependent on the relationship of the LED load voltage and application voltage range. The simplicity of the straight circuit makes many factors mathematically predictable, lending incredible insight into the design process. For the figures below, LED load voltage has been normalized to the peak line voltage, so as to provide the most generalized analysis.

As seen in Figures 8 and 9 below, input power, efficiency, and thermals improve with high load voltages, whereas many other characteristics, including power factor, THD, and dimming performance improve with lower load voltages. It is the careful balancing of these trends that yields a successful design.

Figure 8 below illustrates a few trends that are mathematically predictable, and are determined based upon the behavior of a sine wave compared to a DC level. Figure 8 may be loosely referenced during the design phase when considering very critical parameters, such as efficiency, total current, and power estimation. Figure 9 displays empirically validated trends on a graph as a function of LED voltage, normalized to the bridge voltage peak.

The “Decreasing V_F” and Increasing V_{AC}” scenarios described in Table 1 generally correspond to a shift to the left-ward shift on the Fig. 8 and 9 plots, whereas the “Increasing V_F” and “Decreasing V_{AC}” trends correspond to an increase in normalized forward voltage, and shift the plot point to the right.

These mathematical models neglect circuit and environmental effects on LED forward voltage, such as V_F decrease due to self-heating and rising ambient temperature range, or V_F increase due to ohmic behavior in the LEDs while increasing current. Generally, these parameters change, driver performance can be expected to move up and down these curves.

Figure 10 provides a rough graphical characteristic displaying “critical LED load voltage” as a function of input RMS voltage. The critical LED load voltage, in this case, is a condition for the load voltage below which some protective circuitry will be required for CCR reliability. When LED voltages are low, CCRs experience high peak voltages, and care must be taken so as not to surpass voltage breakdown levels. The plot given in Figure 10 incorporates a 10 V margin on the CCR’s maximum voltage. The equation determining the boundary condition for critical LED load voltage is given in Eq. 3.

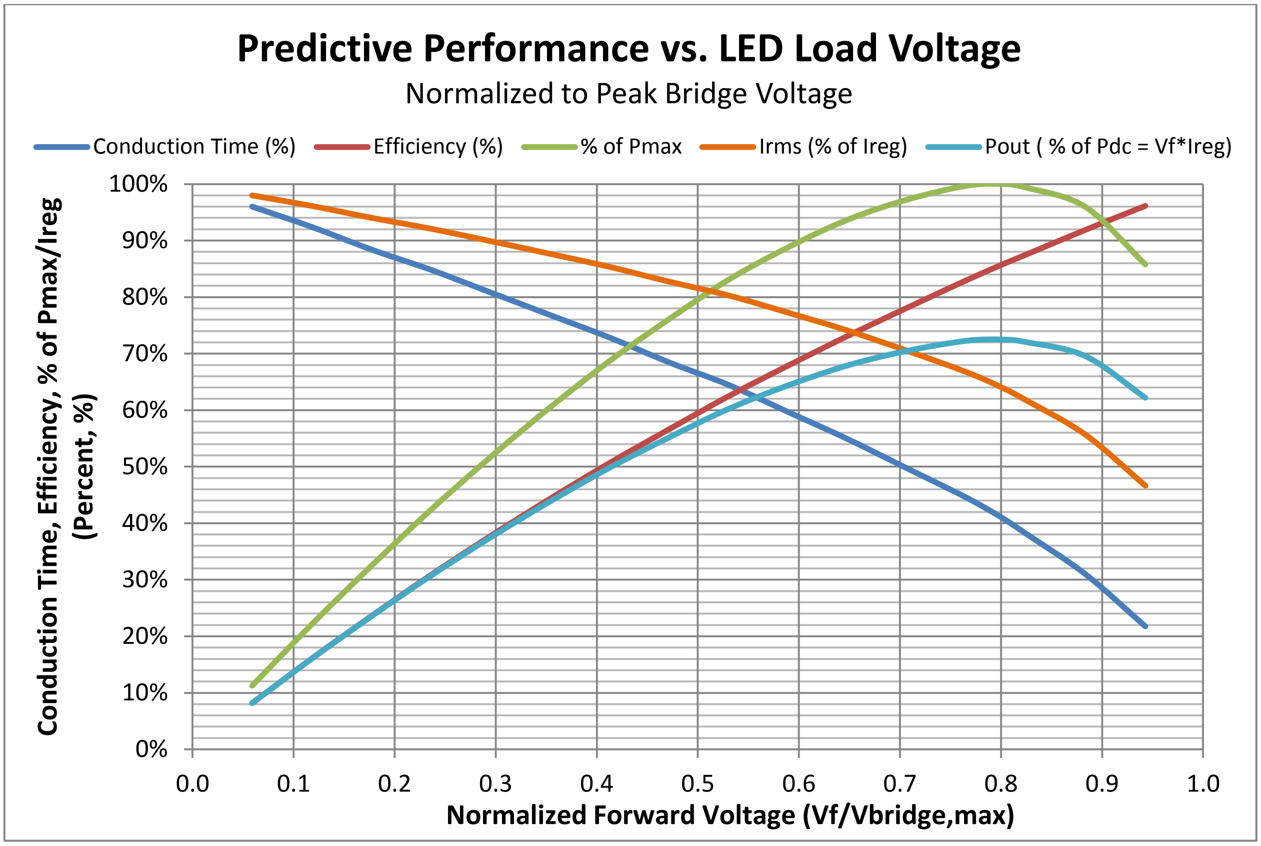

Figure 8: Certain parameters useful in predicting driver performance are mathematically dependent on V_F.

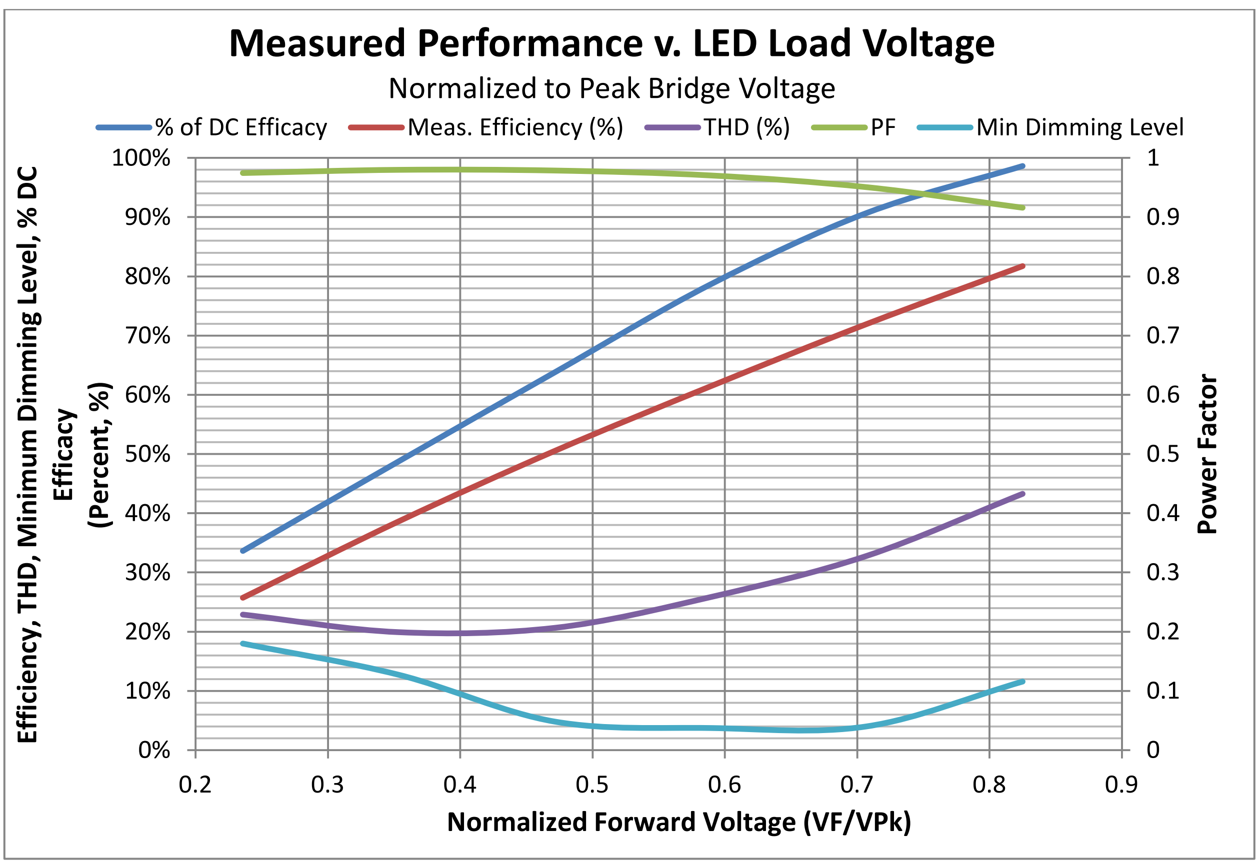

Figure 9: While not necessarily formulaic, real trends of critical performance parameters exist across V_F.

Performance	Decreasing V_F	Increasing V_F	Decreasing V_{AC}	Increasing V_{AC}
$I_{RMS(IN)}$ (mA)	***Small Increase***	Small Decrease	Decrease	***Increase***
PF	***Small Increase***	Small Decrease	Small Decrease	***Small Increase***
THD (I_{RMS}, %)	***Decrease***	Increase	Increase	***Decrease***
P_{IN} (W)	Increase	***Decrease***	***Decrease***	Increase
P_{OUT} (W)	Non-linear	Non-linear	Non-linear	Non-linear
Efficiency (%)	Decrease	***Increase***	***Increase***	Decrease
Min. Dimming Level (%)	***Decrease***	Increase	No effect	No effect
Effective Duty Cycle (%)	***Increase***	Decrease	Decrease	***Increase***
Flicker Index	***Decrease***	Increase	Increase	***Decrease***
CCR Temperature (°C)	Increase	***Decrease***	***Decrease***	Increase

Table 1 – General trends for the circuit shown in Figure 1. Preferred/improved results indicated in shaded boxes.

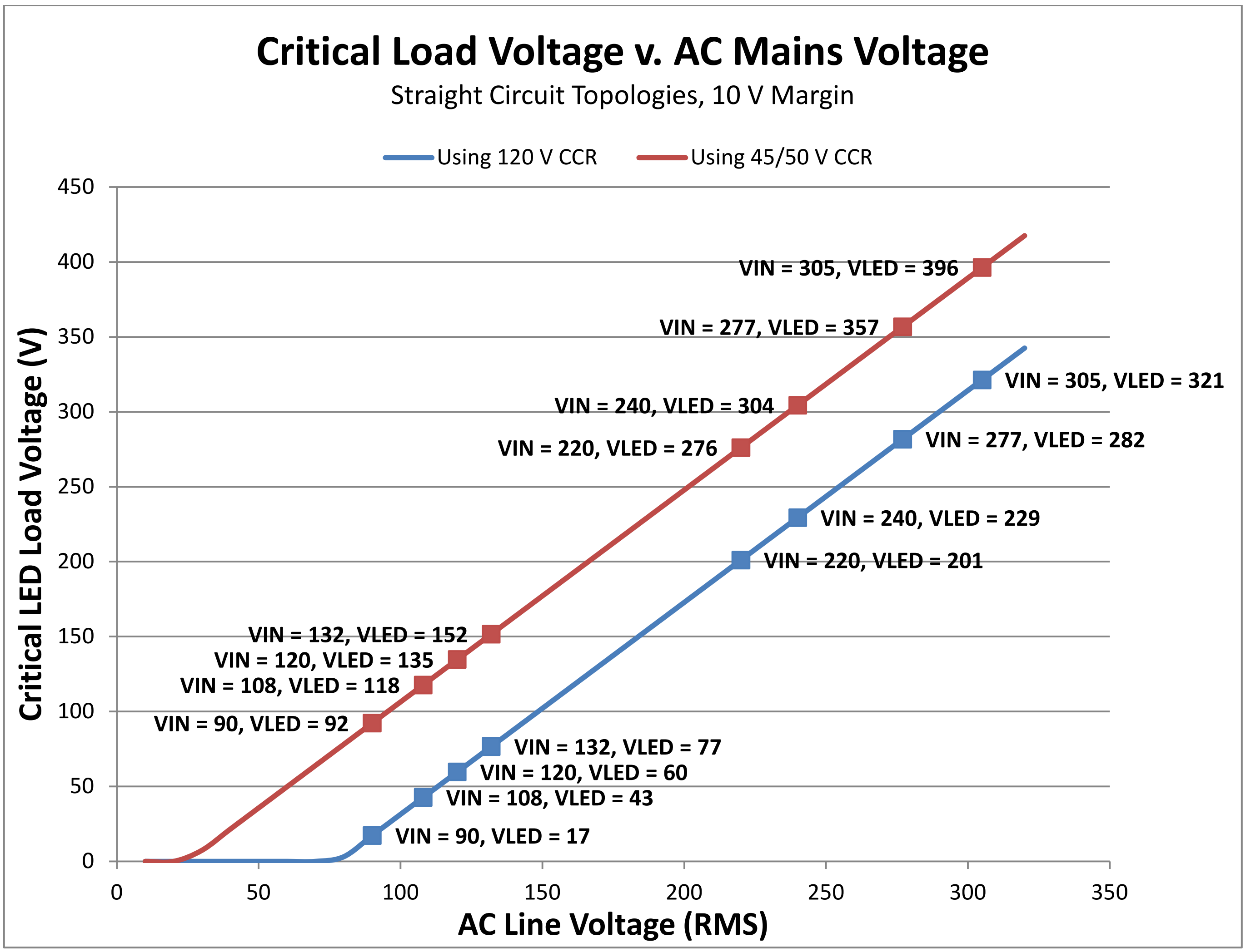

Figure 10: Below the critical LED load voltage, protective circuitry will be needed to keep CCRs within their safe operating regions. The figure above incorporates a 10 V margin from the maximum CCR voltage rating. Source equation is given by Eq. 3 in this technical note.

Case 1: 6 W, 120 V_{AC} Driver Design

Case 1 is a driver design of about 6 W input power, intended for 120 V_{AC} mains. This design does not employ any OVP on the CCR. Depending on the load design, this may be acceptable—use Eq. 3 to determine if OVP is necessary on this circuit. If so, refer to the design in “Case 4” for further guidance.

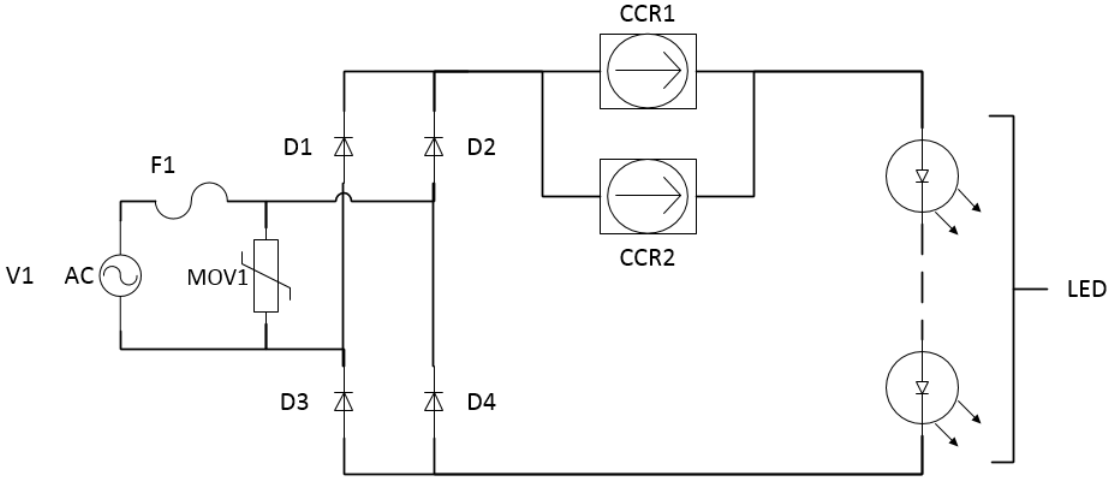

Figure 11 – Schematic of straight circuit without over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1	ON Semi	NSIC2050JB	1	Constant Current Regulator	120 V, 50 mA	±15%
CCR2	ON Semi	NSIC2030JB	1	Constant Current Regulator	120 V, 30 mA	±15%
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	150 V_{AC}	-
D1 – D4	ON Semi	MRA4004	4	Diode	400 V, 1 A	-
LED	Any	-	*	Light-Emitting Diode	120 V, 90 mA	-

* The LED bank design may be composed of a few COB implementations or many single-junction 3V LEDs.

Table 2 – Bill of materials for the circuit shown in Figure 11.

Circuit Data

	108 V_{AC}	114 V_{AC}	120 V_{AC}	126 V_{AC}	132 V_{AC}
$I_{RMS(IN)}$ (mA_{RMS})	58.33	58.67	57.99	57.67	57.09
PF	0.9296	0.9421	0.9521	0.9589	0.9649
THD (I_{RMS}, %)	39.5 %	35.5 %	32.0 %	29.6 %	27.3 %
P_{IN} (W)	5.88 W	6.33 W	6.65 W	6.99 W	7.28 W
P_{OUT} (W)	4.74 W	4.89 W	4.91 W	4.98 W	4.990 W
Efficiency (%)	80.6 %	77.2 %	73.7 %	71.2 %	68.5 %
Min. Dimming Level (%)	3.9 %	3.7 %	3.8 %	3.8 %	3.8 %
Effective Duty Cycle (%)	50.8 %	54.1 %	57.0 %	59.5 %	61.6 %
Flicker Index	0.464	0.434	0.411	0.388	0.373

Table 3 – Electrical characteristics for the circuit shown in Figure 11.

Case 2: 10 W, 120 V_{AC} Driver Design

Case 2 is a driver design of about 10 W input power, intended for 120 V_{AC} mains. This design does not employ any OVP for the CCR. Depending on the load design, this may be acceptable—use Eq. 3 to determine if OVP is necessary on this circuit. If so, refer to Case 4 for further guidance.

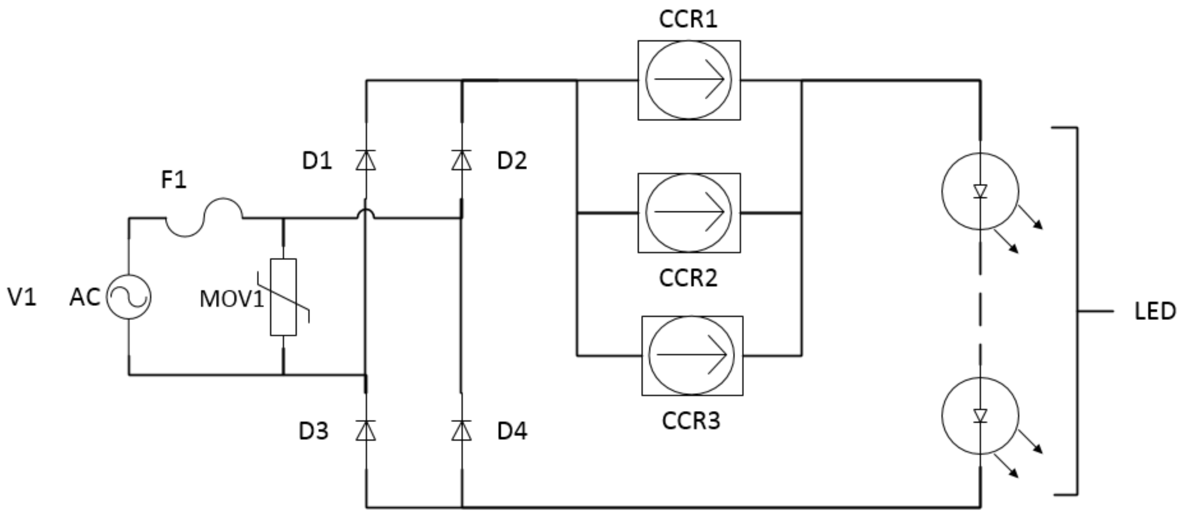

Figure 12 – Schematic of straight circuit without over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1 – 2	ON Semi	NSIC2050JB	2	Constant Current Regulator	120 V, 50 mA	±15%
CCR3	ON Semi	NSIC2030JB	1	Constant Current Regulator	120 V, 30 mA	±15%
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	150 V_{AC}	-
D1 – D4	ON Semi	MRA4004	4	Diode	400 V, 1 A	-
LED	Any	-	*	Light-Emitting Diode	120 V, 130 mA	-

* The LED bank design may be composed of a few COB implementations or many single-junction 3V LEDs.
Table 4 – Bill of materials for the circuit shown in Figure 12.

Circuit Data

	108 V_{AC}	114 V_{AC}	120 V_{AC}	126 V_{AC}	132 V_{AC}
$I_{RMS(IN)}$ (mA)	93.37	94.16	93.13	92.65	91.81
PF	0.9298	0.9424	0.9533	0.9603	0.9657
THD (I_{RMS}, %)	39.40	35.33	31.57	28.96	26.80
P_{IN} (W)	9.391	10.122	10.704	11.220	11.716
P_{OUT} (W)	7.887	8.156	8.107	8.239	8.293
Efficiency (%)	84.0	80.6	75.7	73.4	70.8
Min. Dimming Level (%)	2.8 %	2.8%	2.4 %	2.8%	2.9 %
Effective Duty Cycle (%)	51.23	53.36	56.69	59.90	62.15
Flicker Index	0.46	0.43	0.41	0.38	0.37

Table 5 – Electrical characteristics for the circuit shown in Figure 12.

Case 3: 14 W, 120 V_{AC} Driver Design

Case 3 is a driver design with roughly 14 W nominal input power, intended for 120 V_{AC} mains. This design does not employ any OVP on the CCR. Depending on the load design, this may be acceptable—use Eq. 3 to determine if OVP is necessary on this circuit. If so, refer to Case 4 for further guidance.

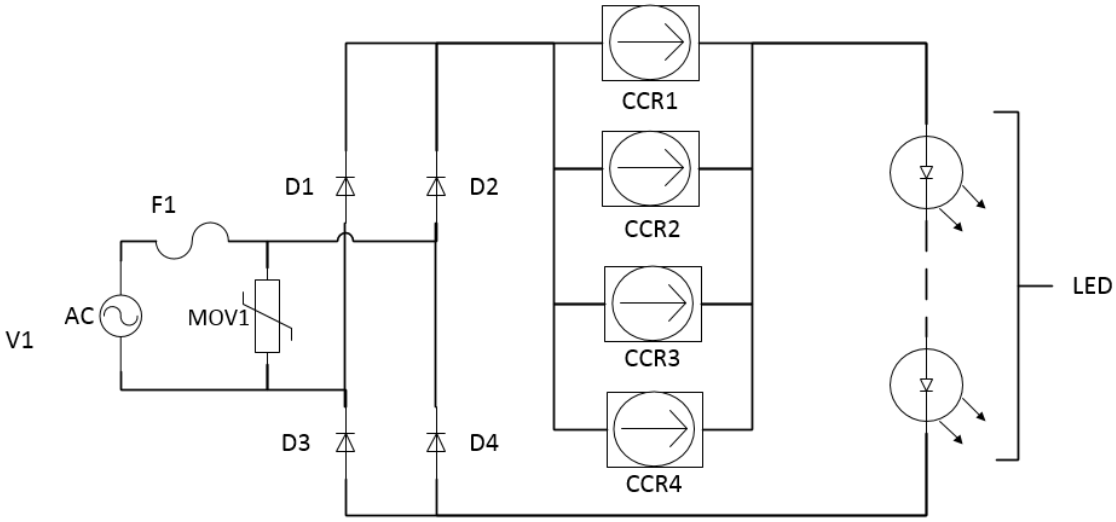

Figure 13 – Schematic of straight circuit without over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1 – 3	ON Semi	NSIC2050JB	3	Constant Current Regulator	120 V, 50 mA	±15%
CCR4	ON Semi	NSIC2030JB	1	Constant Current Regulator	120 V, 30 mA	±15%
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	150 V_{AC}	-
D1 – D4	ON Semi	MRA4004	4	Diode	400 V, 1 A	-
LED	Any	-	*	Light-Emitting Diode	120 V, 180 mA	-

* The LED bank design may be composed of a few COB implementations or many single-junction 3V LEDs.

Table 6 – Bill of materials for the circuit shown in Figure 13.

Circuit Data

	108 V_{AC}	114 V_{AC}	120 V_{AC}	126 V_{AC}	132 V_{AC}
$I_{RMS(IN)}$ (mA)	124.20	124.95	124.30	122.72	120.77
PF	0.924	0.9381	0.949	0.9567	0.9628
THD (I_{RMS}, %)	41.3 %	36.8 %	33.2 %	30.32 %	27.95
P_{IN} (W)	12.49 W	13.36 W	14.13 W	14.787 W	15.324
P_{OUT} (W)	10.33 W	10.62 W	10.76 W	10.768 W	10.734
Efficiency (%)	82.7 %	79.4 %	76.2 %	72.8 %	70.0 %
Min. Dimming Level (%)	2.6 %	2.5 %	2.4 %	2.4 %	2.4 %
Effective Duty Cycle (%)	49.97 %	53.53 %	55.18 %	58.10 %	61.10 %
Flicker Index	0.47	0.44	0.42	0.39	0.38

Table 7 – Electrical characteristics for the circuit shown in Figure 13.

Case 4: 6 W, 230 V_{AC} Driver Design

Case 4 is a driver design of about 6 W input power, intended for 220 – 240 V_{AC} mains. This driver design employs OVP to safely interface the LEDs and CCRs with high line voltages. Depending on the load design, this may or may not be needed—use Eq. 3 to determine if OVP is necessary when driving any LED load.

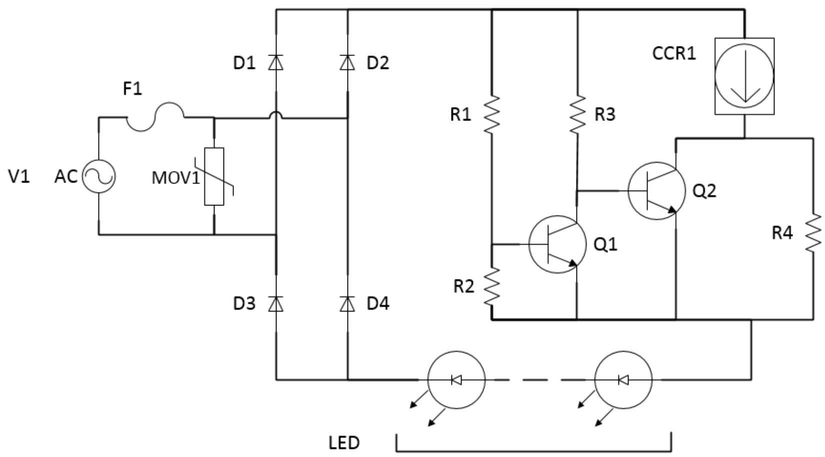

Figure 14 – Schematic of straight circuit LED driver with over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1	ON Semi	NSIC2030JB	1	Constant Current Regulator	120 V, 20 mA	± 15%
R1	Any	-	1	Resistor	1 MΩ, 1/8 W	± 1%
R2	Any	-	1	Resistor	6.8 kΩ, 1/8 W	± 1%
R3	Any	-	1	Resistor	100 kΩ, 1/8 W	± 10%
R4	Any	-	1*	Resistor	3.0 kΩ, ½ W	± 5%
Q1	ON Semi	MMBT3904L	1	NPN Transistor	40 V, 100 mA	-
Q2	ON Semi	NSS1C201L	1	Low $V_{CE,Sat}$ NPN Transistor	100 V, 2.0 A	-
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	300 V_{AC}	-
D1 – D4	ON Semi	MRA4007	4	Diode	1000 V, 1 A	-
LED	Any	-	**	Light-Emitting Diode	120 V, 20 mA	-

* The power resistor may be a single resistor or multiple series/parallel components to optimize cost, space, etc.
** The LED bank design may be composed of a few COBs or many single-junction 3V LEDs.

Table 8 – Bill of materials for the circuit shown in Figure 14.

Circuit Data

	190 V_{AC}	220 V_{AC}	240 V_{AC}	264 V_{AC}	277 V_{AC}
$I_{RMS(IN)}$ (mA)	25.61	27.42	28.25	28.56	28.43
PF	0.946	0.961	0.967	0.975	0.978
THD (I_{RMS}, %)	34.4 %	28.4 %	26.1 %	22.6 %	20.9
P_{IN} (W)	4.616 W	5.82 W	6.57 W	7.36 W	7.71 W
P_{OUT} (W)	3.366 W	4.569 W	5.32 W	5.68 W	5.75 W
Efficiency (%)	72.9 %	78.6 %	80.9 %	77.2 %	74.6
Effective Duty Cycle (%)	54.7 %	62.7 %	66.1 %	69.4 %	71.0 %
Flicker Index	0.42	0.36	0.33	0.29	0.28

Table 9 – Electrical characteristics for the circuit shown in Figure 14.

Case 5: 10 W, 230 V_{AC} Driver Design

Case 1 is a driver design of about 10 W input power, intended for 220 – 240 V_{AC} mains. This design employs a simple OVP scheme to protect the CCR. Depending on the load design, this may not be needed—use Eq. 3 to determine if OVP is necessary on this circuit.

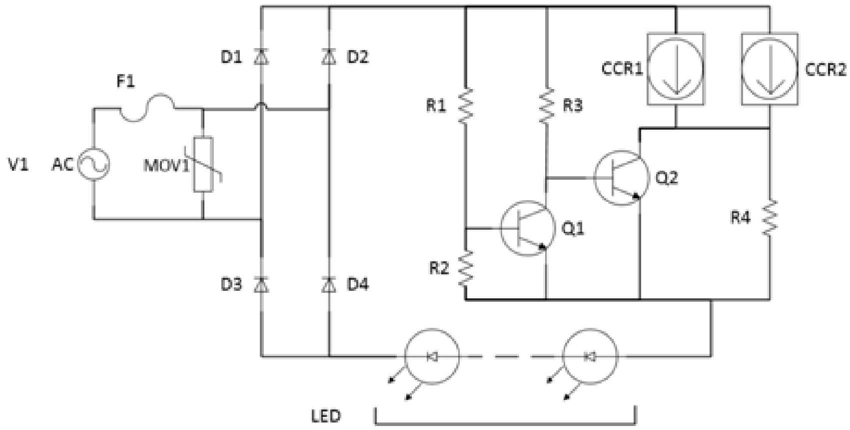

Figure 15 – Schematic of straight circuit with over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1 – 2	ON Semi	NSIC2030JB	2	Constant Current Regulator	120 V, 30 mA	± 15%
R1	Any	-	1	Resistor	1 MΩ, 1/8 W	± 1%
R2	Any	-	1	Resistor	6.8 kΩ, 1/8 W	± 1%
R3	Any	-	1	Resistor	100 kΩ, 1/8 W	± 10%
R4	Any	-	1*	Resistor	1.5 kΩ, 1 W	± 5%
Q1	ON Semi	MMBT3904L	1	NPN Transistor	40 V, 100 mA	-
Q2	ON Semi	NSS1C201L	1	Low $V_{CE,Sat}$ NPN Transistor	100 V, 2.0 A	-
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	300 V_{AC}	-
D1 – D4	ON Semi	MRA4007	4	Diode	1000 V, 1 A	-
LED	Any	-	**	Light-Emitting Diode	120 V, 60 mA	-

* The power resistor may be a single resistor or multiple series/parallel components to optimize cost, space, etc.
** The LED bank design may be composed of a few COBs or many single-junction 3V LEDs.

Table 10 – Bill of materials for the circuit shown in Figure 14.

Circuit Data

	190 V_{AC}	220 V_{AC}	240 V_{AC}	264 V_{AC}	277 V_{AC}
$I_{RMS(IN)}$ (mA)	49.57	52.78	53.79	53.90	53.26
PF	0.941	0.959	0.968	0.976	0.979
THD (I_{RMS}, %)	35.8 %	29.5 %	25.9 %	22.4 %	20.9 %
P_{IN} (W)	8.88 W	11.1 W	12.53 W	13.89 W	14.44 W
P_{OUT} (W)	6.73	9.10 W	9.96 W	10.46 W	10.48 W
Efficiency (%)	75.8 %	82.0 %	79.5 %	75.3 %	72.6 %
Effective Duty Cycle (%)	53.8 %	61.9 %	65.9 %	69.0 %	70.8 %
Flicker Index	0.4104	0.3480	0.3190	0.2889	0.2763

Table 11 – Electrical characteristics for the circuit shown in Figure 15.

Case 6: 14 W, 230 V_{AC} Driver Design

Case 6 is a driver design of about 14 W input power, intended for 220 – 240 V_{AC} mains. This design employs a simple OVP scheme to protect the CCR. Depending on the load design, this may not be needed—use Eq. 3 to determine if OVP is needed on this circuit.

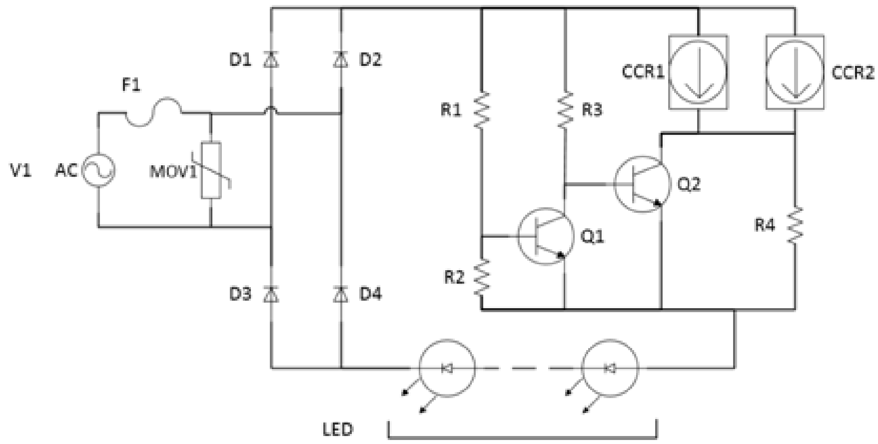

Figure 16 – Schematic of straight circuit with over-voltage protection (OVP).

Bill of Materials

Designator	Manufacturer	Part No.	Qty	Description	Value	Tolerance
CCR1 – 2	ON Semi	NSIC2050JB	2	Constant Current Regulator	120 V, 50 mA	± 15%
R1	Any	-	1	Resistor	1 MΩ, 1/8 W	± 1%
R2	Any	-	1	Resistor	6.8 kΩ, 1/8 W	± 1%
R3	Any	-	1	Resistor	100 kΩ, 1/8 W	± 10%
R4	Any	-	1*	Resistor	910 Ω, ½ W	± 5%
Q1	ON Semi	MMBT3904L	1	NPN Transistor	40 V, 100 mA	-
Q2	ON Semi	NSS1C201L	1	Low $V_{CE,Sat}$ NPN Transistor	100 V, 2.0 A	-
F1	Any	-	1	Fuse	200 V, 1 A	-
MOV1	Any	-	1	Varistor	300 V_{AC}	-
D1 – D4	ON Semi	MRA4007	4	Diode	1000 V, 1 A	-
LED	Any	-	**	Light-Emitting Diode	120 V, 100 mA	-

* The power resistor may be a single resistor or multiple series/parallel components to optimize cost, space, etc.
** The LED bank design may be composed of a few COBs or many single-junction 3V LEDs.

Table 12 **–** Bill of materials for the circuit shown in Figure 14.

Circuit Data

	190 V_{AC}	220 V_{AC}	240 V_{AC}	264 V_{AC}	277 V_{AC}
$I_{RMS(IN)}$ (mA)	59.01	62.73	62.67	61.06	59.33
PF	0.942	0.960	0.969	0.976	0.979
THD (I_{RMS}, %)	35.7 %	29.0 %	25.4 %	22.2 %	20.6 %
P_{IN} (W)	10.59 W	13.29 W	14.60 W	15.74 W	16.07 W
P_{OUT} (W)	8.06 W	10.68 W	11.40 W	11.53 W	11.32 W
Efficiency (%)	76.2 %	80.4 %	78.1 %	73.3 %	70.4 %
Effective Duty Cycle (%)	54.4 %	61.7 %	65.6 %	68.8 %	70.4 %
Flicker Index	0.4276	0.3445	0.3107	0.2831	0.2712

Table 13 **–** Electrical characteristics for the circuit shown in Figure 16.

Further Reference

For similar designs and related material, see the following ON Semiconductor technical publications.

- **Design Note – DN05013/D: Simple ENERGY STAR ® Compliant LED Driver Retrofit in a T5 Tube using 160mA CCR**

  http://www.onsemi.com/pub_link/Collateral/DN05013-D.PDF

- **Application Note – AND9179/D: In-Driver High Voltage Protection Techniques for Constant Current Regulators**

  http://www.onsemi.com/pub_link/Collateral/AND9179-D.PDF

- **Application Note – AND9203/D: Optimizing CCR Protection for Minimal Part Count**

  http://www.onsemi.com/pub_link/Collateral/AND9203-D.PDF

Design note created by Travis Alexander, e-mail: Travis.Alexander@onsemi.com