AN954

Transformerless Power Supplies: Resistive and Capacitive

Author: Reston Condit
Microchip Technology Inc.

INTRODUCTION

There are several ways to convert an AC voltage at a wall receptacle into the DC voltage required by a microcontroller. Traditionally, this has been done with a transformer and rectifier circuit. There are also switching power supply solutions, however, in applications that involve providing a DC voltage to only the microcontroller and a few other low-current devices, transformer-based or switcher-based power supplies may not be cost effective. The reason is that the transformers in transformer-based solutions, and the inductor/MOSFET/controller in switch-based solutions, are expensive and take up a considerable amount of space. This is especially true in the appliance market, where the cost and size of the components surrounding the power supply may be significantly less than the cost of the power supply alone.

Transformerless power supplies provide a low-cost alternative to transformer-based and switcher-based power supplies. The two basic types of transformerless power supplies are resistive and capacitive. This application note will discuss both with a focus on the following:

1. A circuit analysis of the supply.
2. The advantages and disadvantages of each power supply.
3. Additional considerations including safety requirements and trade-offs associated with half-bridge versus full-bridge rectification.

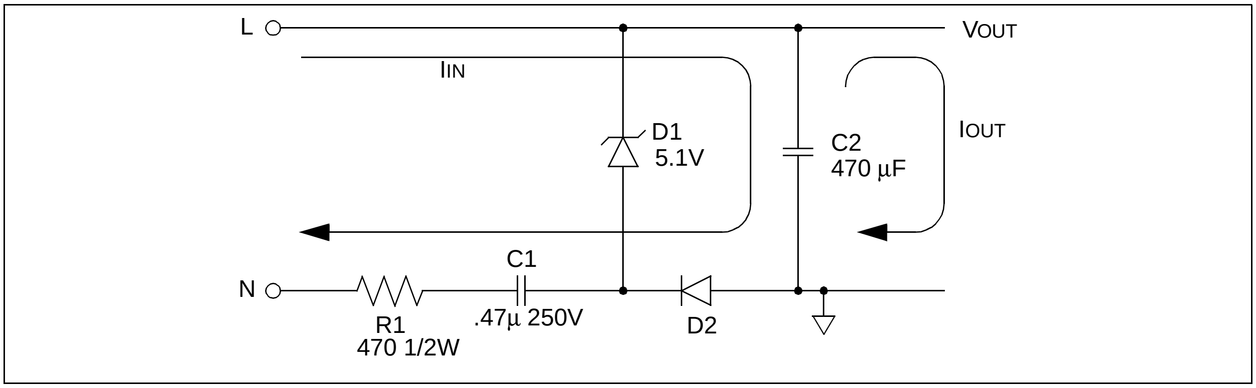
Warning: *An electrocution hazard exists during experimentation with transformerless circuits that interface to wall power. There is no transformer for power-line isolation in the following circuits, so the user must be very careful and assess the risks from line-transients in the user's application. An isolation transformer should be used when probing the following circuits.*

CAPACITIVE TRANSFORMERLESS POWER SUPPLY

A capacitive transformerless power supply is shown in Figure 1. The voltage at the load will remain constant so long as current out (IOUT) is less than or equal to current in (IIN). IIN is limited by R1 and the reactance of C1.

Note:	R1 limits inrush current. The value of R1 is chosen so that it does not dissipate too much power, yet is large enough to limit inrush current.

FIGURE 1: CAPACITIVE POWER SUPPLY



IIN is given by:

EQUATION 1:

$$I_{IN} = \frac{V_{HFRMS}}{X_{C1} + R1} \geq I_{OUT}$$

Where VHFRMS is the RMS voltage of a half-wave AC sine wave and X_{C1} is the reactance of C1.

EQUATION 2:

$$V_{HFRMS} = \frac{V_{PEAK} - V_Z}{2} = \frac{\sqrt{2}V_{RMS} - V_Z}{2}$$

Where VPEAK is the peak voltage of the wall power, VRMS is the rated voltage of wall power (i.e., United States: 115 VAC, Europe: 220 VAC) and VZ is the voltage drop across D1.

EQUATION 3:

$$X_{C1} = \frac{1}{2\pi fC1}$$

Where f is the frequency (i.e., United States: 60 Hz, some countries: 50 Hz).

Substituting Equation 2 and Equation 3 into Equation 1 results in:

EQUATION 4:

$$I_{IN} = \frac{\sqrt{2}V_{RMS} - V_Z}{2\left(\frac{1}{2\pi fC1} + R1\right)}$$

The minimum value of I_{IN} should be calculated for the application, while the maximum value of I_{IN} should be calculated for the power requirements of individual components.

EXAMPLE 1: CALCULATE MINIMUM POSSIBLE I_{IN}

Assume minimum values of all components except V_Z and R1. Assume maximum value of V_Z and R1.

- V_{RMS} = 110 VAC
- V_Z = 5.1V
- f = 59.5 Hz
- C = C1 = 0.47 µF x 0.8 = 0.38 µF (assuming ±20% capacitor)
- R = R1 = 470 x 1.1 = 517 (assuming ±10% resistor)
- I_{INMIN} = 10.4 mA

EXAMPLE 2: CALCULATE MAXIMUM POSSIBLE I_{IN}

Assume maximum values of all components except V_Z and R1. Assume minimum value of V_Z and R1.

- V_{RMS} = 120 VAC
- V_Z = 5V
- f = 60.1 Hz
- C = C1 = 0.47 µF x 1.20 = 0.56 µF (assuming ±20% capacitor)
- R = R1 = 470 x 0.9 = 423 (assuming ±10% resistor)

I_{INMAX} = 16.0 mA

V_{OUT} is given by:

EQUATION 5:

$$V_{OUT} = V_Z - V_D$$

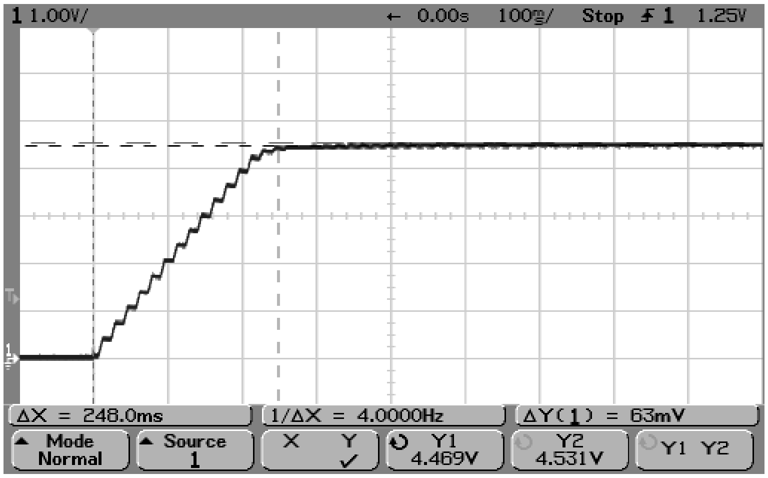
Where V_D is the forward voltage drop across D2.

Assuming a 5.1V zener diode and a 0.6V drop across D2, the output voltage will be around 4.5V. This is well within the voltage specification for PIC® microcontrollers.

OBSERVATIONS

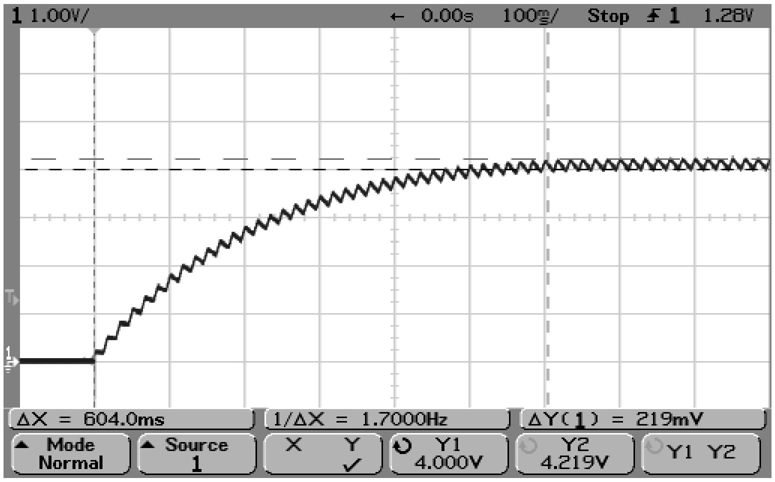
Figure 2 shows an oscilloscope plot of V_{OUT} at power-up with a 10 kΩ load on the output (between V_{OUT} and ground.) The 10 kΩ load draws only 0.45 mA. As a result, the rise time of V_{OUT} is 280 ms (as fast as possible for given I_{IN} and C2), ripple is minimal when V_{OUT} stabilizes at the voltage calculated in Equation 5, approximately 4.5V.

FIGURE 2: V_{OUT} AT START-UP WITH 10 KΩ LOAD



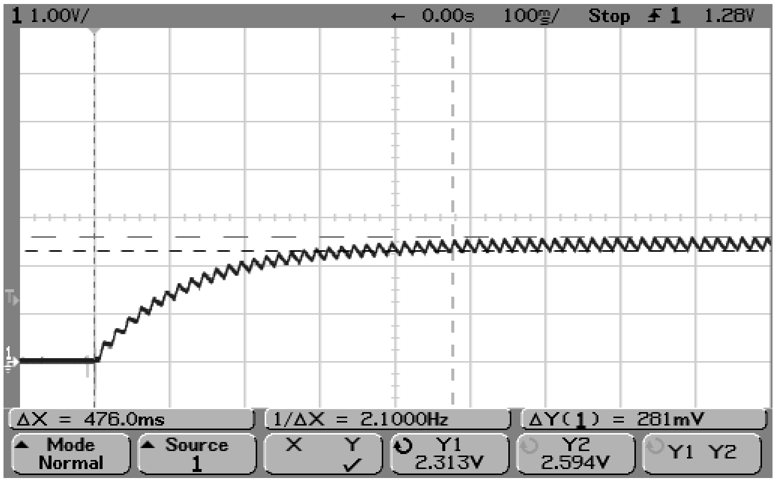
If the load is increased, the behavior of the circuit changes in several ways. Figure 3 shows an oscilloscope plot of VOUT during the same time frame for a 500Ω load. A 500Ω load draws 9 mA at 4.5V. This is near the 10.4 mA limit calculated in Example 1. The rise time of VOUT is longer (680 ms) as expected because not only is IOUT charging C2, but a significant amount of current is being drawn by the load. VOUT stabilizes at approximately 4.1V, about four tenths of a volt below the output voltage calculated in Equation 5. The ripple on VOUT is more pronounced with the increased current draw.

FIGURE 3: VOUT AT START-UP WITH 500 Ω LOAD



If even more current is demanded from the circuit, the supply will stabilize at a voltage below the desired level. Figure 4, shows an oscilloscope plot of VOUT during the same time frame for a 270Ω load. A 270Ω load will draw approximately 16 mA with an output voltage of 4.5V. This current cannot be provided by the circuit, therefore, the output voltage is compromised.

FIGURE 4: VOUT AT START-UP WITH A 270 Ω LOAD



POWER CONSIDERATIONS

Determining the power dissipation of the components in the circuit is a critical consideration. As a general rule, components should be selected with power ratings at least twice the maximum power calculated for each part. For AC components, the maximum RMS values of both voltage and current are used to calculate the power requirements.

Sizing R1:

The current through R1 is the full-wave current. This current is equivalent to the line voltage divided by the impedance of C1.

EQUATION 6:

$$P_{R1} = I^2R = (V_{RMS}*2\pi fC)^2R1$$

$$= (21.3\ mA)^2(470\Omega\ x\ 1.1) = 0.23W$$

(assuming ±10% resistor)

Doubling this gives 0.46W, so a 1/2W resistor is sufficient.

Sizing C1:

Assuming a maximum wall voltage of 120 VAC, double this is 240V. A 250V X2 class capacitor will suffice.

Note: The class of X2 capacitor is intended for use in applications defined by IEC664 installation category II. This category covers applications using line voltages from 150 to 250 AC (nominal).

Sizing D1:

D1 will be subjected to the most current if no load is present. Assuming this worst case condition, D1 will be subjected to approximately the full-wave current once C2 is charged. This current was calculated when sizing R1 (see above).

EQUATION 7:

$$P_{D1} = IxV = (21.3\ mA)(5.1V) = 0.089W$$

Doubling this exceeds 1/4W, so a 1/2W 5.1V zener diode is a good choice.

Sizing D2:

The maximum RMS current that will flow through D2 was calculated in Example 2. Assuming a 0.7V drop across the resistor for half the wave, the following equation (over) approximates the power dissipated in D2.

EQUATION 8:

$$P_{D2} = IxV = (16.0\ mA)(0.7V) = 0.011W$$

A 1/8 W rectifier is sufficient for D2.

Sizing C2:

C2 should be rated at twice the voltage of the zener diode. In this case, a 16V electrolytic capacitor will work. C2 simply stores current for release to the load. It is sized based on the ripple that is acceptable in V_{OUT}. V_{OUT} with decay according to Equation 9.

EQUATION 9:

$$V_{out} = V_d\, e^{\frac{-t}{RC}}$$

V_D was calculated in Equation 5

Advantages and Disadvantages

Advantages of Capacitive Power Supply:

1. Significantly smaller than a transformer-based power supply.
2. More cost effective than a transformer-based or switcher-based power supply.
3. Power supply is more efficient than a resistive transformerless power supply (discussed next).

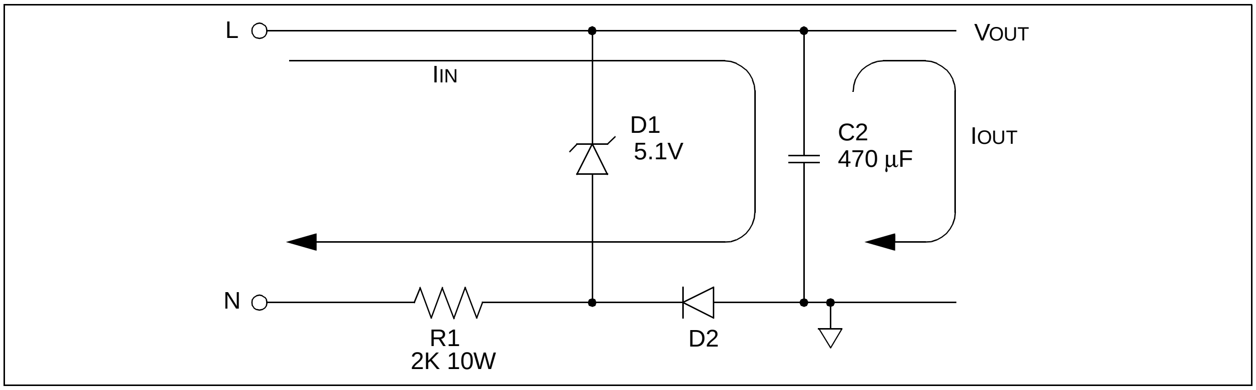
Disadvantages of Capacitive Power Supply:

1. Not isolated from the AC line voltage which introduces safety issues.
2. Higher cost than a resistive power supply.

RESISTIVE TRANSFORMERLESS POWER SUPPLY

A basic resistive transformerless power supply is shown in Figure 5. Instead of using reactance to limit current, this power supply simply uses resistance. As with the capacitive power supply, V_{OUT} will remain stable as long as current out (I_{OUT}) is less than or equal to current in (I_{IN}.)

FIGURE 5: RESISTIVE POWER SUPPLY



I_{IN} is given by:

EQUATION 10:

$$I_{IN} = \frac{V_{HFRMS}}{R1} \geq I_{OUT}$$

Where V_{HFRMS} is the RMS voltage of a half-wave AC sine wave.

EQUATION 11:

$$V_{HFRMS} = \frac{V_{PEAK} - V_Z}{2} = \frac{\sqrt{2}V_{RMS} - V_Z}{2}$$

Where V_{PEAK} is the peak voltage of the wall power, V_{RMS} is the rated voltage of wall power (i.e., United States: 115 VAC, Europe: 220 VAC), and V_Z is the voltage drop across D1.

Substituting Equation 11 into Equation 10 results in:

EQUATION 12:

$$I_{IN} = \frac{\sqrt{2}V_{RMS} - V_Z}{2R1}$$

The minimum value of I_{IN} should be calculated for the application while the maximum value of I_{IN} should be calculated for power requirements.

EXAMPLE 3: CALCULATE MINIMUM POSSIBLE I_{IN}

Assume minimum value of V_{RMS}. Assume maximum value of V_Z and R.

- V_{RMS} = 110 VAC
- V_Z = 5.1V
- R = R1 = 2 kΩ x 1.1 = 2.2 kΩ (assuming ±10% resistor)

I_{INMIN} = 34.2 mA

EXAMPLE 4: CALCULATE MAXIMUM POSSIBLE I_{IN}

Assume maximum value of V_{RMS}. Assume minimum value of V_Z and R.

- V_{RMS} = 120 VAC
- V_Z = 5V
- R = R1 = 2 kΩ x 0.9 = 1.8 kΩ (assuming ±10% resistor)

I_{INMIN} = 45.8 mA

V_{OUT} is the same as given for the capacitive power supply (see Equation 5).

OBSERVATIONS

The observations for the resistive power supply are very similar to the capacitive power supply. Please refer to the “Observations” in **Section “Capacitive Transformerless Power Supply”** for more details.

Figure 6, Figure 7 and Figure 8 show VOUT at start-up for the resistive power supply with loads of 10 kΩ, 270Ω and 100Ω, respectively. These loads correspond to output currents of 0.45 mA, 16 mA and 45 mA, respectively, assuming an output voltage of 4.5V. Clearly VOUT is not 4.5V in Figure 6 because the current demand placed on the power supply is too high.

FIGURE 6: VOUT AT START-UP WITH 10 KΩ LO AD

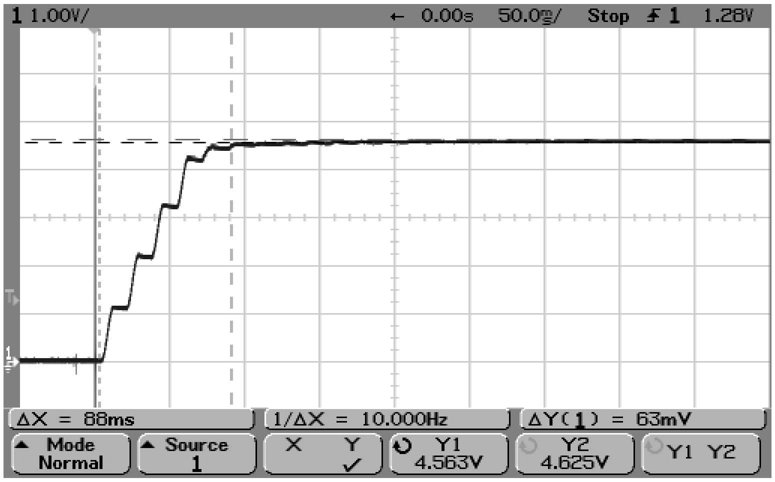


FIGURE 7: VOUT AT START-UP WITH 270Ω LOAD

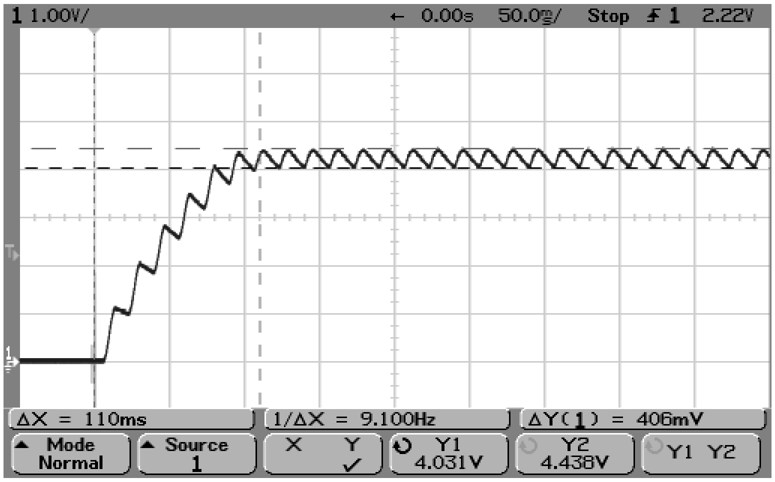
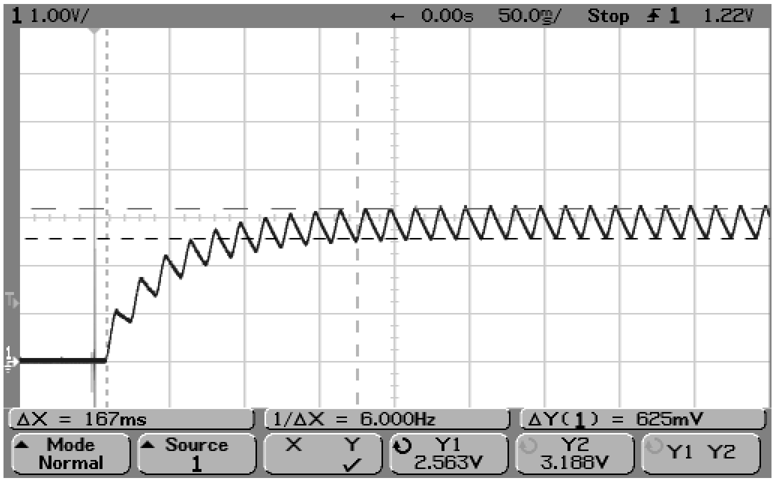


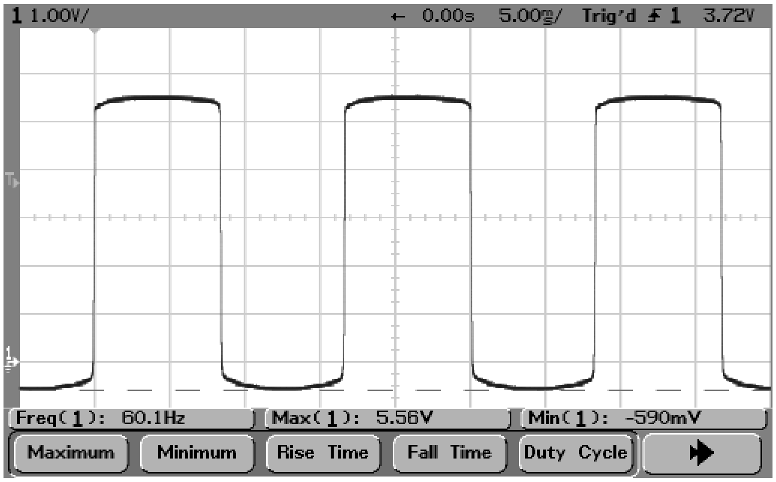
FIGURE 8: VOUT AT START-UP WITH 100Ω LOAD



When working with an 60 Hz AC source, it is often desirable to know when the line voltage crosses Neutral. The crossing, known as zero-cross, can easily be captured by connecting the node formed by D1, C1 and D2 to an input on the microcontroller. The waveform observed at this node is shown in Figure 9.

For the resistive power supply, the transition in this waveform occurs at the zero-cross. For capacitive supplies, some delay is present due to the in-series capacitor (C1 in Figure 1).

FIGURE 9: FIGURE A: WAVEFORM AT ZERO CROSS NODE



POWER CONSIDERATIONS

Selecting component power rating in the circuit is a critical consideration. As a general rule, components should be sized at twice the maximum power calculated for each device. For the AC components, the RMS values of both voltage and current are used to calculate the power requirements.

Sizing R1:

EQUATION 13:

$$P_{R1} = I^2R = \frac{V^2}{R}$$

$$\left(\frac{120^2}{2\ k\Omega\ x\ 0.9}\right) = 8W$$

(assuming ±10% resistor)

A 10W resistor builds in 2 watts of safety so it will be used.

Sizing D1:

With no load, the current through D1 will be approximately equal to the full wave current through R1.

EQUATION 14:

$$P_{D1} = Vx1 = V_Z\ \frac{V_{RMS}}{R1}$$

$$5.1V\left(\frac{120}{2\ k\Omega\ x\ 0.9}\right) = 0.34W$$

A 1 W 5.1V zener diode should be used.

Sizing D2:

The maximum RMS current that will flow through D2 was calculated in Example 4. Assuming a 0.7V drop across the resistor for half the wave, the following equation (over) approximates the power dissipated in D2.

EQUATION 15:

$$P_{D2} = IxV = (45.8\ mA)(0.7V) = 0.032W$$

A 1/8W diode is a sufficient for D2.

Sizing C2:

C2 should be rated at twice the voltage of the zener diode. In this case, a 16V electrolytic capacitor will work. C2 simply stores current for release to the load. It is sized based on the voltage fluctuations that are acceptable on V_{OUT}. V_{OUT} decays according to Equation 9.

Advantages and Disadvantages

Advantages of Resistive Power Supply:

1. Significantly smaller than a transformer-based power supply.
2. Lower cost than a transformer-based power supply.
3. Lower cost than a capacitive power supply.

Disadvantages of Resistive Power Supply:

1. Not isolated from the AC line voltage which introduces safety issues.
2. Power supply is less energy efficient than a capacitive power supply.
3. Loss energy is dissipated as heat in R1.

OTHER CONSIDERATIONS

Safety Considerations

> ***Disclaimer:*** *This section does not provide all the information needed to meet UL requirements. UL requirements are application specific and are not exclusive to the circuit design itself. Some of the other characteristics that are factors in meeting UL requirements are trace width, trace proximity to one another, and (but not limited to) other layout requirements. Visit the Underwriters Laboratories Inc. Web page at www.ul.com for more information.*

FIGURE 10: CAPACITIVE POWER SUPPLY WITH SAFETY CONSIDERATIONS

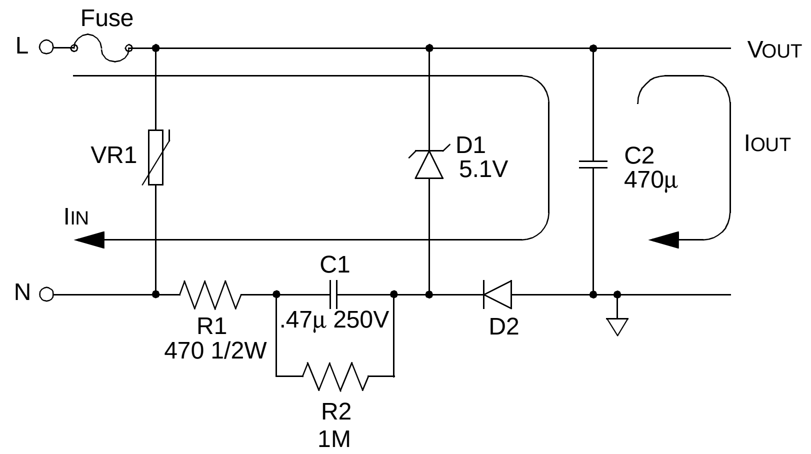
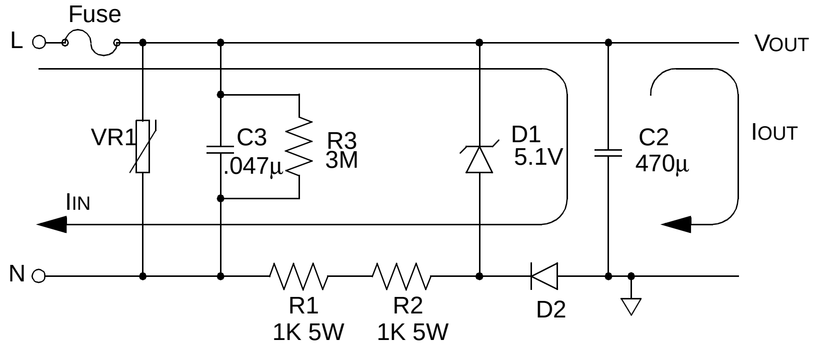


Figure 10 shows a capacitive power supply with several UL considerations designed in. A fuse is added to protect the circuit during an over-current condition. Adding R2 in parallel with C1 creates a filter that will attenuate EMI from traveling back onto the line. A varistor, or MOV, provides transient protection.

Figure 11 shows a resistive power supply with several UL considerations[1] designed in.

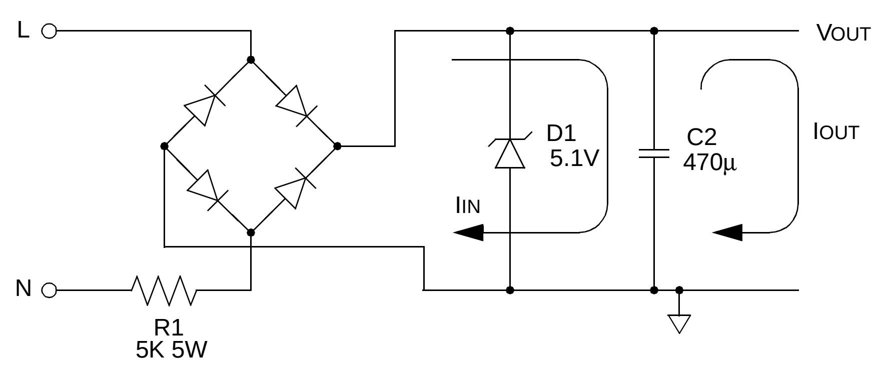
> **Note 1:** User must research applicable UL specifications that apply to the user's specific product. Products must be tested by a certified lab to make sure all UL requirements are met.

FIGURE 11: RESISTIVE POWER SUPPLY WITH SAFETY CONSIDERATIONS



As with the capacitive power supply, a fuse and varistor have been added to provide over current and transient protection respectively. The 2 kΩ resistor is separated into two 1 kΩ in-series resistors. Series resistors should be split into two resistors so that a high voltage transient will not bypass the resistor. The use of the two resistors also lowers the potential across the resistors, reducing the possibility of arcing. C3 and R3 create a filter which prevents EMI created by the circuit from migrating onto the Line or Neutral busses.

FIGURE 12: RESISTIVE POWER SUPPLY WITH BRIDGE RECTIFIER



Bridge Rectification

The current output of each of the circuits described can be increased by 141% with the addition of a low-cost bridge rectifier. Figure 12 shows what the resistive power supply looks like with this addition.

Instead of providing current during only one half of the AC waveform period, current is supplied by the source during both halves. Equation 16 gives the RMS voltage for the full wave RMS voltage seen across R1.

EQUATION 16:

$$V_{FLRMS} = \frac{\sqrt{2}V_{RMS} - V_Z}{\sqrt{2}}$$

Substituting into Equation 10 gives an equation for I_{IN}:

EQUATION 17:

$$I_{IN} = \frac{\sqrt{2}V_{RMS} - V_Z}{\sqrt{2}R}$$

Advantages of bridge rectifier over half-wave rectifier:

1. Provides 141% more current.
2. More efficient.
3. V_{OUT} is more stable.

Disadvantages of bridge rectifier compared to half-wave rectifier:

1. More expensive.
2. V_{OUT} is not referenced to just line or neutral making triac control impossible.