Designing a Capacitive Charge Pump Power Supply

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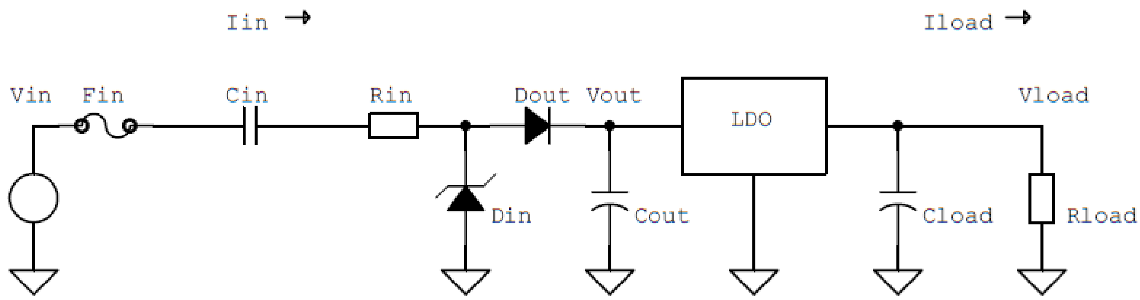
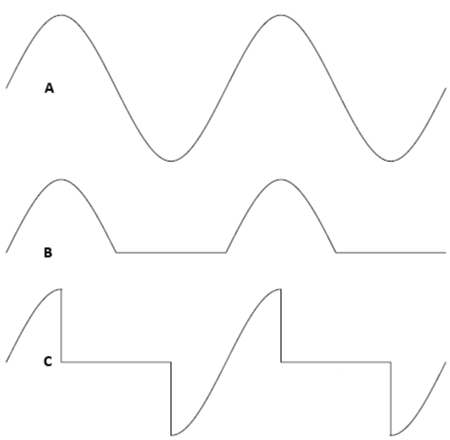
Circuit

The basic circuit is shown below and is the classic non-isolated AC to DC capacitive converter. It works just fine and provides a simple and low-cost solution for many products. There's just one thing – every application note I've read explains it wrong!



Rectification

The circuit employs half-wave rectification. Other application notes show how the input AC voltage sinewave A gets rectified into something like waveform B. Well, that's just plain incorrect. This is a current mode converter, not voltage! The portion of input sinewave actually being rectified is shown in waveform C. The rising voltage injects a current into the output via capacitor C_{in}. Not only that, but current reaches a maximum as the input voltage crosses through zero, not at the voltage peaks.



Derivation

For the purposes of understanding the method of operation, let's ignore D_{out} and everything to the right of it. We can also ignore the fuse F_{in} and resistor R_{in}, as they serve no purpose under normal conditions.

As the input voltage rises, a current is injected into D_{in} defined as

$$I_{in} = \frac{V_{av}}{Z_{in}}$$

The impedance Z_{in} is defined by

$$Z_{in} = \frac{1}{2 \cdot \pi \cdot f \cdot C_{in}}$$

As we are looking to determine the *average* input current (C_{out} will store charge and smooth the output voltage), we start by obtaining the average input voltage. For half wave rectification, this is given by

$$|V_{av}| = \frac{V_p}{\pi} = \frac{\sqrt{2} \cdot V_{in}}{\pi}$$

This equation remains true even though we are using waveform C. One thing we need to note is that the negative and positive peak voltages across C_{in} are not the same. During the "off" half of the cycle, current is pulled out of D_{in}. Therefore, the negative peak voltage is reduced by the amount of V_D, with D_{in} forward biased. For the "on" half of the cycle, current pushes into D_{in} resulting in a positive peak reduced by V_Z.

Combining the above equations, we get

$$I_{in} = \frac{V_{av}}{Z_{in}} = \frac{\left(\frac{\sqrt{2} \cdot V_{in} - V_Z}{2 \cdot \pi}\right) + \left(\frac{\sqrt{2} \cdot V_{in} - V_D}{2 \cdot \pi}\right)}{\left(\frac{1}{2 \cdot \pi \cdot f \cdot C_{in}}\right)} = f \cdot C_{in}\left(2\sqrt{2} \cdot V_{in} - V_Z - V_D\right)$$

This is the full cycle *average* input current. We can take advantage that the peak AC input voltage is many times greater than any practical zener voltage (typically we want something like a 5V output), which simplifies the formula to

$$I_{in} \approx 2\sqrt{2} \cdot V_{in} \cdot f \cdot C_{in}$$

Re-arranging this we solve for C_{in}

$$C_{in} \approx \frac{I_{in}}{2\sqrt{2} \cdot V_{in} \cdot f}$$

For an application running at 120V and 60Hz this simplifies to (with C_{in} given in μF)

$$\boxed{C_{in} \approx 50 \cdot I_{in}}$$

C_{in} should be a good quality film capacitor that can handle the bipolar ripple currents and voltages. Polyester is a good choice; polypropylene is even better.

Voltage

The input current is turned into an output voltage via the zener. The circuit will fall out of regulation if the load current is too high, and must be less than the average input current. Under these conditions, maximum output voltage is

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

C_{out} is used to filter the discontinuous input current into a smooth output voltage, where the ripple is dependent on the load current. The value of this filtering capacitor is determined by

$$C_{out} = \frac{i \cdot t}{V} = \frac{I_{load}}{f \cdot V}$$

For a 60Hz system with a voltage ripple of 1V, this simplifies to

$$\boxed{C_{out} \approx \frac{I_{load}}{60}}$$

Regulation

Most applications will require a regulated output voltage. An LDO type is perfect for this design, as we don't want to burn any extra unnecessary power across the regulator. For a 5V output with 1V ripple on C_{out}, then V_{out} should be at least 6V. Taking into account the forward voltage drop across D_{out}, the minimum zener voltage should be 6.8V.

Protection

Since this supply is powered directly from AC mains, the capacitor C_{in} should have an appropriate safety rating. In other words, it needs to fail as an open circuit, not a short. When such a capacitor cannot be found in the required value, adding a fuse will sidestep the issue. That is why F_{in} is shown in the circuit.

Similarly, R_{in} is only there for surge protection. Under normal conditions it is not needed, but when there is a voltage surge (ESD, lightning, etc.), the peak current through C_{in} and D_{in} may exceed their ratings. To solve this the resistor R_{in} is added. But what value should it be? I'm proposing a value that is 5% of the impedance of C_{in}. This will provide some level of protection without significantly altering circuit performance.

$$R_{in} = \frac{1}{40 \cdot \pi \cdot f \cdot C_{in}}$$

For a 60Hz system this simplifies to (with C_{in} given in µF)

$$\boxed{R_{in} \approx \frac{130}{C_{in}}}$$

The power dissipation in this resistor is determined by the input current. However, I_{in} is given for a full cycle average. Since the entire charge is pumped during half a cycle (half-wave rectification), that value is actually double. And it is the same, but in the opposite direction for the other half of the cycle (current that isn't being used except to charge C_{in}). Therefore, the power dissipation in the resistor is

$$\boxed{P_R = \left(2 \cdot I_{in}\right)^2 \cdot R_{in}}$$

In a practical application, the resistor should have a rating of at least 3x this to keep temperatures reasonable.

<u>Example</u>

Let's say we have a need to power a 5V circuit at up to 75mA. Step one is to set I_{in} slightly higher, to prevent dropouts. Let's chose 80mA. We then get

$$C_{in} = 50 \cdot I_{in} = 50(0.08) = 4uF$$

Let's select a value of 4.7µF to buy us some headroom against low input voltage and component tolerance. Again our choice for zener voltage is 6.8V. The minimum filter capacitor needs to be

$$C_{out} = \frac{I_{load}}{60} = \frac{(0.075)}{60} = 12{,}500\mu F$$

The series resistor calculates to

$$R_{in} = \frac{130}{C_{in}} = \frac{130}{4.7} = 27\Omega$$

Power dissipation in the resistor is

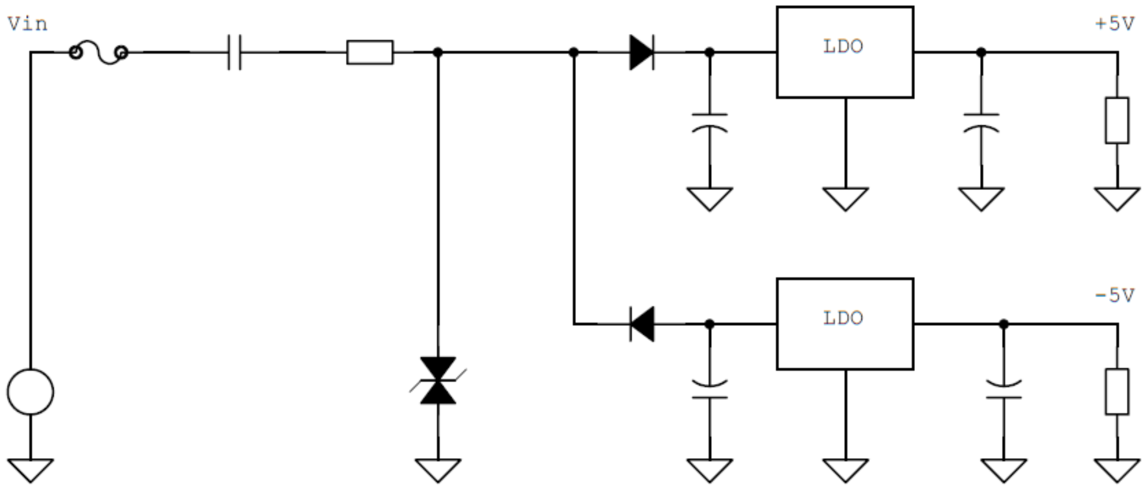
$$P_R = (2 \cdot I_{in})^2 \cdot R_{in} = (2 \cdot 0.08)^2 \cdot 27 = 0.7W$$

Similarly the power dissipation in the zener diode can be as high as 0.54 watts, if the load current drops to zero. In summary, for a practical design we get

Component	Value	Rating
C_{in}	4.7µF	250VAC
R_{in}	27Ω	2W
C_{out}	15,000µF	10V
V_Z	6.8V	2W

Dual Supply

As we noted earlier, the "off" portion of the cycle burns just as much input current as the "on" portion. We can use this! By adding just a few more components we can add a negative supply. This is often useful, especially if one desires to power analog circuitry.



The key to dual supplies is to install back-to-back zener diodes. The output voltage V_{out} is now equal to the zener voltage. Everything else calculates the same. Using dual outputs doubles the overall conversion efficiency of the supply.