Transformerless Power Supply Design

General Description

Transformerless AC power supplies accept wall-outlet AC voltage (such as 120VAC) input and produce a low voltage DC (such as 3VDC) output. The low voltage DC is typically low current output, on the order of tens of milliamps.

This DesignNote explains how transformerless power supplies work and examines tradeoffs to consider when designing them. The options described herein can be implemented with the **ProtoPowerSwitch**, a circuit for prototyping products that control AC voltage and/or are powered by AC voltage.

The ProtoPowerSwitch can be ordered pre-populated or as a bare board. Beyond the prototyping stage, Designer Circuits, LLC can support transition to production by designing and sourcing custom circuit boards specific to your application. Contact info@designercircuits.com to learn more.

Transformerless AC Power Supplies

Transformerless AC power supply theory is not generally taught at the university level, yet the use of such power supplies is prevalent in consumer goods. Online whitepapers and websites provide example circuits and equations to aid the design process, yet these sources emphasize the math without explaining the fundamental principles of operation. The aim of this DesignNote is familiarize the reader with the basic concepts, such that the equations can be derived, constructed, and manipulated intuitively.

The scope of this document addresses circuits which accept single phase AC voltage (e.g. 120VAC, 240VAC) and output low, fixed DC voltage.

Basic Concept

A transformerless power supply typically incorporates:

- Rectification
- Voltage Division
- Regulation
- Filtering
- Inrush Limiting

Described simply, the AC input voltage charges up an output filter capacitor. The AC voltage is rectified to ensure that the capacitor is only charged and not discharged by the mains. Voltage division ensures that only a small fraction of the input voltage shows up across the output capacitor. Lastly, a Zener diode in parallel with the output capacitor performs basic voltage regulation.

Rectification

The first step in the process is to rectify the high voltage AC sinusoid such that the remainder of the circuit is only ever exposed to positive voltage. This is achieved by passing the sinusoid through either (1) a full bridge rectifier composed of four diodes, or (2) a single diode that blocks the negative part of the sinusoidal voltage, as shown in Figure 1.
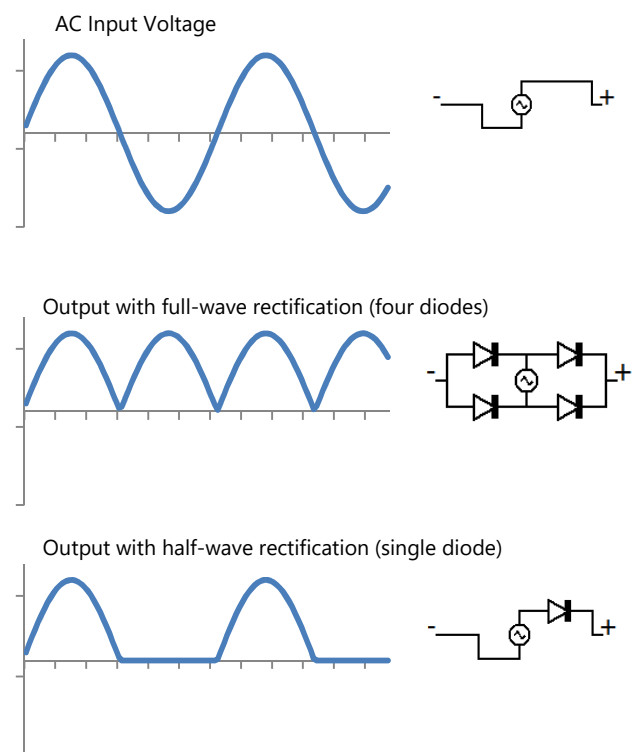

AC Input Voltage

Output with full-wave rectification (four diodes)

Output with half-wave rectification (single diode)

Figure 1 Input and Output Waveforms for Full- and Half-Wave Rectification Stages

Regardless of the configuration, diodes comprise the rectification stage. In the following sections, the rectified output voltage waveform will be referred to simply as V_{in}.

Using a High Voltage to Make a Low Voltage

A well-known method of generating a low voltage from a high voltage is to use a voltage divider circuit, as shown in Figure 2. In textbook examples, the impedances Z_1 and Z_2 are typically resistors, and if only negligible current leaves through V_{out}, then the voltage we can expect at V_{out} is $V_{in} * Z_2 / (Z_1 + Z_2)$.
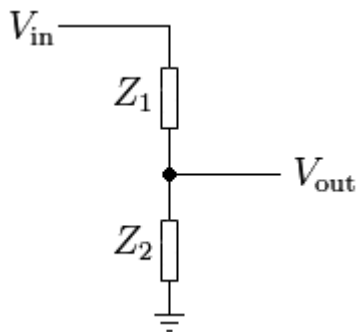

Figure 2 Basic Voltage Divider Circuit

Using resistors for both Z_1 and Z_2 will generally result in a poor power supply design. Good power supplies support a range of output current from V_{out} while holding the output voltage constant. In a resistor-based design, if there is *any* load current then the voltage drop across Z_1 will increase and V_{out} will correspondingly decrease, which is undesirable. Another issue is that if V_{in} were to decrease, then V_{out} will decrease by the same proportion. Given that V_{in} varies significantly over time (see Figure 1), we know with certainty that V_{out} will also vary over time as well, which is again undesirable.

To improve the performance of the power supply, we can replace the Z_2 resistor with a Zener diode instead, as shown in Figure 3
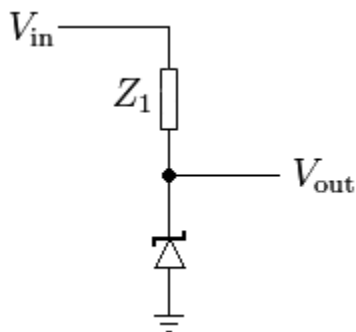

Figure 3 Voltage Divider Circuit with Zener

An ordinary diode will pass current in one direction (indicated by the arrow of the symbol) but will block current if it tries to flow the other way, preferring instead to allow a reverse voltage to build up across it. The *Zener* diode has the unusual characteristic that above a specified reverse voltage (the Zener voltage) for the device, it will no longer block current but instead allow current to flow through it in

reverse. This reverse current flow occurs only when the reverse voltage across the Zener diode grows high enough to match the Zener voltage rating.

Note that the Zener diode will actively dissipate power when reverse current flows through it because there is a voltage (the Zener voltage) across it. This power is $P = I*V$.

Using a Zener diode instead of a resistor for Z_2 produces a better power supply which maintains constant output voltage despite changes in input voltage or load current. Regardless of whether 1mA or 30mA is flowing through the Zener diode, its Zener voltage does not change (much). Thus, V_{out} also will not change, even if a load connected to V_{out} draws current (current that would have otherwise passed through the Zener diode).

If the small amount of inherent Zener diode voltage variability is unacceptable, V_{out} can feed into an LDO or DC/DC power supply, which will provide improved output regulation.

Constant Power Loss

The Zener diode introduces a non-obvious drawback common to all transformerless power supplies: **constant power consumption regardless of load**. The current passing through Z_1 can go one of two places: through the Zener diode or through the load connected to V_{out}. However, the total average current will always match the current through Z_1. For a transformerless supply that can source up to 30mA:

- If the load connected to V_{out} draws very little current (or none at all), then all unused current (up to 30mA) flows through Z_2 which dissipates power in the Zener diode.
- If the load connected to V_{out} draws most of the 30mA, then the power dissipation of the Zener is lower while the power dissipation of the load is higher.

> ⚠️ *Constant average input power input is incurred for a transformerless power supply regardless of whether or not the load draws current.*

Output (Hold-up) Capacitance

A rectified sinusoidal AC input voltage (as shown in Figure 1) has periods of time where the instantaneous V_{in} has a smaller magnitude than the DC output (Zener) voltage. To prop up the DC output voltage during these periods, a capacitor is added to V_{out}. This capacitor allows V_{out} to "ride through" the periods of small instantaneous AC voltage.

Input Impedance

Z_1 is usually implemented as one of two options. A very simple low cost Z_1 is a **resistor**; a more efficient option is a **capacitor**. The size of the Z_1 resistor or capacitor and the Zener voltage together determine how much total output current will be available.

Blocking Diode Placement

There are two places where blocking diode(s) for rectification can be placed: before the Zener diode and after the Zener diode.

In general, placing a blocking diode after the Zener ("post-Zener") will prevent the (admittedly small) reverse current flow from the output capacitor through the Zener. The output capacitor generates reverse current flow through the Zener only during portions of the waveform where V_{in} is less than the output capacitor voltage. Inclusion of a Post-Zener diode results in a tradeoff that the output voltage will typically be a diode drop (0.7V) less than the Zener voltage.

Full Wave Rectified Circuits:

For full-wave rectification to be effective, the rectification must be performed before the Zener diode (that is, the full bridge rectifier must be between the AC source and the Zener diode). This is because the Zener diode will only generate the Zener voltage output whenever a reverse voltage is applied to it. Full wave rectification ensures that Vin is positive, which allows the Zener voltage to be generated. If full wave rectification were added after the Zener diode (between the Zener and the output capacitor), then the negative portion of the AC waveform would simply result in forward conduction through the Zener, which does not generate a useful output voltage. Therefore, for full-wave rectification, blocking diodes must *always* be present before the Zener diode ("pre-Zener"). An optional blocking diode may still be placed after the Zener. However, in full wave rectified circuits this is typically not done; the opportunity for the output capacitor to discharge through the Zener in reverse occurs so infrequently that that the leakage is not a concern.

Half Wave Rectified Circuits:

If half wave rectification is used, a single post-Zener blocking diode may be used with no pre-Zener blocking diode. Post-Zener blocking diodes provide greater benefit in a half wave rectified circuit because (as shown in the waveform of Figure 1) at least 50% of the time, V_{in} sits at 0V, which is less than the output voltage, giving plenty of opportunity for capacitor leakage through the Zener. The leakage is even more evident in low voltage Zener diodes (<6V typically) because their current-voltage curve tends to be "softer"—that is, the Zener may start conducting current well before the Zener voltage is reached. In many cases, however, the leakage currents even without a Post-Zener blocking diode is usually low enough that it is not a concern.

Resistive And Capacitive Input Impedance

As mentioned previously, there are both resistive and capacitive options for the input impedance selection. The purpose of the input impedance is to provide a large voltage drop from V_{in} to V_{out}. For *resistive* input impedance, it should come as no surprise that this large voltage drop generates substantial power loss when compared against *capacitive* input impedance.

Table 1 provides a comprehensive list of the basic transformerless power supply configurations, along with the tradeoffs encountered by each configuration.

The basic configurations are constructed from the following options:

- Capacitive or Resistive Input Impedance
- Full Wave or Half Wave Rectification
- Pre-Zener or Post-Zener Rectification

Note that full-wave configurations with post-Zener rectification are entirely excluded from the list because it is not possible to generate full-wave rectification after the Zener has effectively passed only a half-wave rectified output.

The Capacitive Half-Wave Rectified configuration with Pre-Zener Rectification is shown for illustrative purposes only as it does not generate output voltage.

Resistive Transformerless AC Supply

The lowest-cost, physically-smallest component we can use for input impedance Z_1 is a resistor, which we will refer to as R_1 or R_{in}. All load and Zener diode current flows through R_1. Large peak voltages (as high as $V_{in,peak}$ - V_{out}) will exist across R_1, so it must be rated to handle high voltage. The combination of high voltage and current flow (equal to the total load + Zener current) results in significant power lost as heat in resistor R_1. A resistive transformerless is typically sized to deliver relatively small amounts of current (a few mA) so as to limit the heat generated by resistor R_1.
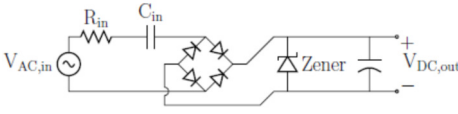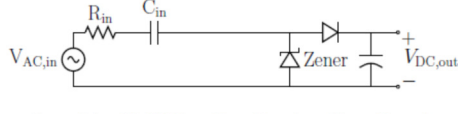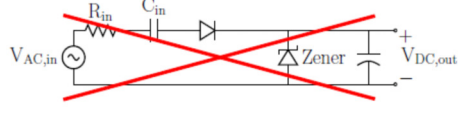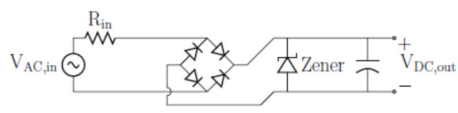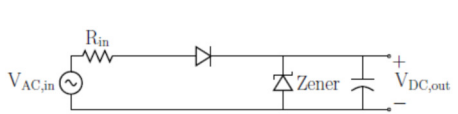
The power dissipated by resistor R_1 for a full-wave rectifier is the RMS voltage across R_1 squared, divided by the resistance R_1. We can approximate the RMS voltage across R1 from the RMS of the input voltage minus the DC output voltage.

$$P_{loss,R_1} = \frac{(V_{in,RMS} - V_{out})^2}{R_1}$$

> ⚠️ *The equations in the **Microchip Application Note AN954 (revision A), Transformerless Power Supplies: Resistive and Capacitive** and **ST Application Note AN2263** have fundamental errors and the reader is encouraged to use the corrected equations provided here, and to verify designs through simulation as well.*

Table 1. Transformerless Power Supply Configurations and Tradeoffs

Circuit	Tradeoffs
 Capacitive Full Wave Rectification (Pre-Zener)	-More efficient than resistive -Physically larger and higher material cost than resistive -Provides twice the output current of the half-wave capacitive -DC output ground not tied to AC neutral; *cannot* drive SCRs/TRIACs directly
 Capacitive Half Wave Rectification (Post-Zener)	-More efficient than resistive -Physically larger and higher material cost than resistive -Provides half the output current of the full-wave capacitive -DC output ground tied to AC neutral; SCRs/TRIACs can be driven directly -No reverse current loss from output capacitor through Zener
 Capacitive Half Wave Rectification (Pre-Zener)	Simply does not work. Output current for capacitive supply is determined by $i_{out} = C_{in}\frac{dv}{dt}$. The diode blocks capacitor C_{in} from discharging, so $dv = 0$ and thus $i_{out} = 0$
 Resistive Full Wave Rectification (Pre-Zener)	-Less efficient than capacitive (significant heat generated by R_{in}) -Physically smaller and lower material cost than capacitive -Provides twice the output current of the half-wave resistive -DC output ground not tied to AC neutral; *cannot* drive SCRs/TRIACs directly -R_{in} power loss is twice as much as resistive half-wave pre-Zener -Slight reverse current loss from output capacitor through Zener (can be mitigated with additional blocking diode)
 Resistive Half Wave Rectification (Post-Zener)	-Less efficient than capacitive (significant heat generated by R_{in}) -Physically smaller and lower material cost than capacitive -Provides half the output current of the full-wave resistive -DC output ground tied to AC neutral; SCR/TRIACs can be driven directly -Output blocking diode drop reduces V_{out} below Zener voltage -R_{in} power loss is twice as much as resistive half-wave pre-Zener -No reverse current loss from output capacitor through Zener
 Resistive Half Wave Rectification (Pre-Zener)	-Less efficient than capacitive (significant heat generated by R_{in}) -Physically smaller and lower material cost than capacitive -Provides half the output current of the full-wave resistive -DC output ground tied to AC neutral; SCR/TRIACs can be driven directly -V_{out} is not reduced by the presence of a blocking diode -R_{in} power loss is half as much as resistive half-wave post-Zener -Slight reverse current loss from output capacitor through Zener (can be mitigated with additional blocking diode)

For a half-wave rectifier with the blocking diode pre-zener, the effective input RMS voltage is reduced:

$$P_{loss,R_1} = \frac{(\frac{V_{in,RMS}}{\sqrt{2}} - V_{out})^2}{R_1}$$

All current that flows through R_1 has the potential to become output current. It is only when the Zener diode conducts current that the current is lost as heat in the Zener. Otherwise, the output capacitor effectively stores the R_1 current, which allows loads to draw current from the output capacitor as needed. Based on capacitor charge (amp-second) balance principles, we know that the output capacitor will provide as many amp-seconds to the load as it receives from R_1. Thus, the average current through R_1 represents the maximum average output current that the resistive transformerless power supply can generate. The word "maximum" is used here because less current can always be delivered to the output (down to 0A), in which case the Zener consumes the unused current.

R_1 will pass an average current based on the average voltage applied across it. For a full wave rectified AC input, this means the output current will be based on the average of the absolute value of the AC waveform. Looking back at Figure 1 for the full wave output, we see that simply calculating the average AC voltage for the positive ½ of one sine wave period will provide the average AC voltage for the entire waveform.

$$i_{out,max,fullwave} = \frac{\left(\frac{\int_0^\pi (V_{pk}\sin\theta - V_{Zener})d\theta}{\pi - 0}\right)}{R_1}$$

$$i_{out,max,fullwave} = \frac{V_{pk}((-\cos\pi) - (-\cos 0)) - V_{Zener}(\pi - 0)}{R_1\pi}$$

$$i_{out,max,fullwave} = \frac{V_{pk}(1 - (-1)) - \pi V_{Zener}}{R_1\pi}$$

$$i_{out,max,fullwave} = \frac{2V_{pk} - \pi V_{Zener}}{R_1\pi}$$

$$i_{out,max,fullwave} = \frac{0.637V_{pk} - V_{Zener}}{R_1}$$

For a half wave rectified AC input instead, the output current will be half of the average of the positive part of the AC waveform (because the other half of the waveform will be 0V). This reduces the average output current by exactly half compared to the full wave rectified configuration.

$$i_{out,max,halfwave} = \frac{(0.318V_{pk} - 0.5V_{Zener})}{R_1}$$

This method of calculation will generally result in a value within a few percent of the actual circuit. This precision is usually adequate, because there are more significant factors affecting circuit performance, like capacitance variability and line voltage variability.

Advanced calculation: If a more accurate calculation is required, the equations in this section may be used. The voltage measured across the resistor R_1 is reduced by the output voltage. For small output voltages (less than 10V) it is reasonable to use V_{pk}-V_{zener} whereas for large output voltages >10V, simulation is preferred because the voltage across R_1 begins looking less and less like a normal sinusoid; the current through (and voltage across) R_1 is zero while the AC line voltage is less than the zener voltage.

As before, the AC input sinusoid is represented by $V_{pk}\sin\theta$. Current only enters the circuit when that voltage exceeds V_{Zener}, so we can subtract out V_{Zener} at all points. However we will only want to consider the voltages where the sinusoid voltage exceeds the Zener voltage, because that is the time when current is being conducted through R_1. This brings in the limits of integration in slightly from both 0 and pi. The sine of the angle at which the sinusoid exceeds the Zener voltage will be V_{zener}/V_{pk}, so the starting limit for integration will be $\theta = \sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)$. The area we are interested in integrating over is shown graphically below.
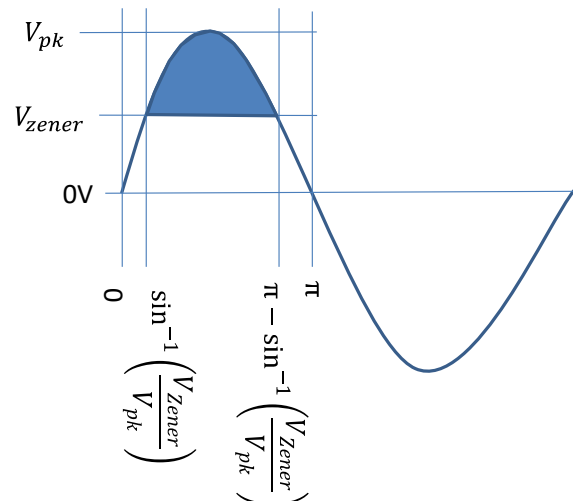
That integration, divided by the full period of π, gives us the average voltage seen by R_1. We can divide the result by R1 to get the average current that passes through R_1, and this average current is used to charge the output capacitor. Because the capacitor amp-seconds in and amp-seconds out must balance, this average R_1 current also represents the maximum current we can get out of the circuit.

The complete equation for full wave rectification is thus:

$$i_{out,max,fullwave} = \frac{\left(\frac{\int_{\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)}^{\pi - \sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)} (V_{pk}\sin\theta - V_{Zener})d\theta}{\pi - 0}\right)}{R_1}$$

Note that the equation above neglects any pre- and post-blocking diode voltage drop for simplicity, but this can be lumped into V_{zener} if desired. For half wave rectification, the

only change is that denominator $\pi - 0$ becomes $2\pi - 0$ (because the input current pattern repeats every 360 degrees = 2π instead of every 180 degrees = π.

$$i_{out,max,halfwave} = \frac{\left(\frac{\int_{\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)}^{\pi-\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)}\left(V_{pk}\sin\theta - V_{Zener}\right)d\theta}{2\pi - 0}\right)}{R_1}$$

In all cases (fullwave or halfwave), the worst-case heat generated by a Zener diode is

$$P_{loss,Zener} = V_{zener}i_{out,max}$$

And the worst-case heat generated by R_1 is

$$P_{loss,R_1} = i_{out,max}^2 R_1$$

Device tolerances and safety margin (typically reducing power ratings of components by 50%) should be considered when sizing components for power loss. Further guidance for worst-case power sizing is provided in the notes of the accompanying spreadsheet.

Capacitive Transformerless AC Supply

Typically a capacitive transformerless supply is used to delivery larger amounts of current (tens of milliamps) than resistive transformerless supplies, specifically because the improved efficiency enables it without additional cooling concerns.

If we use a capacitor (C_1 or C_{in}) for input impedance Z_1, the efficiency improves because we are no longer "losing to heat" the current that was flowing through it when Z_1 was resistive. Rather, the amp-seconds are stored in the capacitance of C_1 without loss, and then C_1 is discharged without loss. Instead of the output current being related to $\frac{V_{pk}}{R_1}$, it is related to $C_1\frac{dV(t)}{dt}$.

Input Resistance for Inrush Limiting

Despite the naturally reduced losses for the capacitive transformerless supply, resistive loss is still added back in intentionally. As for why: if a capacitor is connected directly to the mains at an instant when the AC voltage is at a peak value, the large voltage will rapidly charge up the capacitor, which appears (albeit briefly) to be a short circuit. The high current that charges up the capacitance can potentially exceed upstream circuit breaker current limits, causing them to trip and generate localized power outages. Additionally, the high inrush current can cause undesirable arcing at the moment the device is plugged in. To prevent high inrush currents, a small resistance is usually placed in series with C_1. The resistance should be small enough that it does not generate much heat, but should be large enough that it limits short circuit currents to acceptable levels. Common 120VAC household circuit breakers in the US are typically rated for 15A. If 5A is an acceptable maximum short circuit

current, then the resistance should be no less than R_1 = Vpk/5A = 170V/5A = 34Ω. For the inrush current to remain less than 0.4A, then R_1 = 470Ω will do nicely.

$$i_{short\ circuit,max} = \frac{V_{pk}}{R_1}$$

The steady state power loss (as heat) incurred by this additional resistance will based on be the maximum output current of the supply.

$$P_{R_1} = i_{out,max}^2 R_1$$

For capacitive transformerless power supplies, there is a tradeoff between reducing inrush current and reducing power consumed by the resistor.

If the transformerless power supply is designed for a maximum output current of 30mA, then R_1 = 34Ω (for 5A max inrush current) will generate 0.03W of heat, while inrush current will be limited to . Likewise, R_1 = 470Ω (for 0.4A max inrush current) will generate just under 0.5W of heat.

Sizing the Input Capacitor

The input capacitor size determines how much output current available will be available from the capacitive transformerless power supply. The capacitor must be capable of handling positive and negative voltage (so no aluminum electrolytics!). To meet UL safety requirements, the capacitor [must be rated for use in series with the mains](#), which is typically a poly film capacitor.

The larger the input capacitor, the greater the output current, according to the well-known relationship:

$$i = C\frac{dv}{dt} \quad \text{or for this application:} \quad i_{C_1} \sim C_1 \frac{dV_{C_1}(t)}{dt}$$

However, the inrush-limiting input resistance R_1 also provides some impedance which effectively reduces the voltage presented to the capacitor. To calculate the maximum output current, a method very similar to the resistive power supply is used, but R_1 is replaced by with the combined impedance of the resistor and capacitor, Z_1. The equation to calculate output current for a full wave-rectified capacitive transformerless power supply is:

$$i_{out,max,fullwave} = \frac{0.637V_{pk} - V_{Zener}}{Z_1}$$

$$i_{out,max,fullwave} = \frac{0.637V_{pk} - V_{Zener}}{\sqrt{(R_1)^2 + \left(\frac{1}{2\pi f C_1}\right)^2}}$$

> ⚠️ *The above equation supersedes "Equation 1" in Microchip's AN954A, and "Equation 1" of ST's AN2263. Those application notes are incorrect for this equation. The average voltage of the waveform should be used (as in 0.637*V_{peak}) instead of the RMS value. Also, their method to sum the impedances incorrectly ignores that R and C impedances are orthogonal—the Pythagorean Theorem should be used in the denominator.*

As before, feel free to use the more comprehensive version of the equation with more accurate integration limits and including the voltage drop of blocking diodes. Be aware that designs which require too much accuracy will likely have too little design margin to operate robustly in the real world, full of device tolerances, temperature variability, and line voltage sags.

$$i_{out,max,fullwave} = \frac{\left(\frac{\int_{\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)}^{\pi-\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)} \left(V_{pk} - V_{Zener}\right) \sin\theta \, d\theta}{\pi - 0} \right)}{\sqrt{(R_1)^2 + \left(\frac{1}{2\pi f C_1}\right)^2}}$$

The equation for a half wave rectified capacitive transformerless power supply is also very similar, having only half the output current of the full wave version:

$$i_{out,max,halfwafe} = \frac{\left(0.318 V_{pk} - 0.5 V_{Zener}\right)}{\sqrt{(R_1)^2 + \left(\frac{1}{2\pi f C_1}\right)^2}}$$

and the more comprehensive version:

$$i_{out,max,halfwave} = \frac{\left(\frac{\int_{\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)}^{\pi-\sin^{-1}\left(\frac{V_{Zener}}{V_{pk}}\right)} \left(V_{pk} - V_{Zener}\right) \sin\theta \, d\theta}{2\pi - 0} \right)}{\sqrt{(R_1)^2 + \left(\frac{1}{2\pi f C_1}\right)^2}}$$

Sizing the Input Resistance

The input resistance will limit inrush current, but will also consume power. Unfortunately, the added impedance also reduces the available output current. The "Input Resistor Tradeoff" worksheet in the spreadsheet that accompanies this document helps to compare these competing objectives of resistor power consumption, output current, and worst-case inrush current.

As a general rule of thumb, most applications achieve a reasonable balance when the percentage of resistive impedance is around 10% of the input capacitor impedance:

$$(R_1)^2 \cong \frac{1}{10}\left(\frac{1}{2\pi f C_1}\right)^2$$

Input Capacitor Safe Discharge

When a capacitive transformerless power supply is disconnected from the AC mains, there is no guarantee that the capacitor will be in a discharged state. This creates a high voltage safety hazard on a circuit that would normally be presumed as safe when disconnected. To mitigate this concern, a high value resistor is usually places in parallel with the capacitor. A 1MΩ will typically suffice. The resistor needs to be rated to handle at least the peak voltage of the circuit.

Advanced Performance Considerations

Other considerations one may make when designing transformerless power supplies include output voltage ripple, support for multiple output voltages, power loss in the Zener diodes, and when to use full wave vs. half wave rectification.

Output Ripple

With 60Hz AC input voltage, the output capacitor will have 60Hz ripple for a half wave rectified circuit, and 120Hz ripple for a full wave rectified circuit. For the same rated output current, the full wave rectified circuit will have half as much output ripple as the half wave rectified circuit. The peak voltage of the ripple will be at the Zener voltage, which should be taken into consideration when observing maximum and minimum voltage thresholds of the load.

The magnitude of voltage ripple will vary directly with the amount of load current; more load current will result in a higher magnitude of voltage ripple. Simulation is recommended to determine whether the expected ripple is acceptable.

For applications which generate greater-than-desired ripple, the output can be conditioned with an LDO or small DC-DC power converter, both of which provide power supply ripple rejection (PSRR). When using an LDO, the Zener should be about 1 to 2V above the LDO output voltage to ensure that the minimum dropout limit is met.

When using a DC-DC converter on the output of the transformerless power supply, there is an opportunity to significantly vary the voltage being fed to the DC-DC converter, which allows for greater output currents. With a transformerless power supply, current is typically limited to a few tens of mA because of resistive heat losses. The average maximum output current must flow through a resistor (either input impedance resistor or inrush limiting resistor) with high voltage across it, which can generate substantial heat on the order of watts.

If a step-down DC-DC converter is used on the output of a transformerless power supply, a higher output voltage (e.g.

24VDC) can be reduced to the desired voltage (e.g. 3.0VDC) efficiently, allowing more low voltage current to be available, even reasonably upwards of 100mA. In such applications, the heat generated by the Zener diode (under no-load conditions) may then become the limiting constraint. This benefit, as well as the reduced output ripple, should be considered against the higher cost of adding a DC-DC converter.

Zener Power Dissipation

The Zener will dissipate power in this circuit. In the worst case-scenario (when the load current is zero) the maximum current for the transformerless supply is being passed through the Zener diode. The power dissipation in the Zener will be the Zener voltage multiplied by the rated output current of the transformerless supply. Thus, the higher the Zener voltage and the higher the power rating of the supply, the more heat the Zener will generate.

$$P_{Zener,max} = V_{Zener}I_{out,max}$$

It is critical to note the thermal properties of the Zener diodes to ensure they will meet desired performance at the temperature they will operate at. If necessary, per-Zener power dissipation can be reduced by using multiple Zener diodes in series, but this comes at the cost of increased part count and board space claim.

Multiple Outputs

A transformerless power supply is capable of generating multiple output voltages simultaneously. This is done by stacking up Zener diodes in series and then tapping off the desired voltages. Each series-connected Zener is independently capable of providing the maximum rated output current. For example, a 30mA circuit that provides both 3.3V and 24V output through a 3.3V and 24V Zener (respectively) will be able to source 30mA for both outputs independently; the tradeoff is that the ground/return of one circuit will be tied to the high side of the other circuit, as shown below:
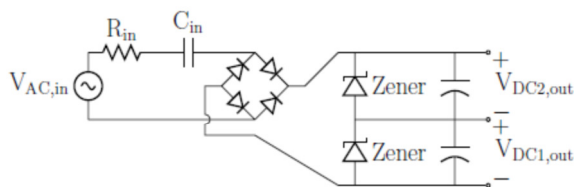
Transformerless Supply with Dual Output Zeners

There are several scenarios in which stacking Zener diodes can be very useful:

Powering a microcontroller and relay coil: A low voltage output can be generated to operate a microcontroller, which then controls a 24V relay coil though an optoisolator. Typically, low voltage relay coils consume far too much current for a transformerless supply, whereas this method enables relay control of a higher voltage coil that consumes less current.

Bipolar voltage generation: For circuits requiring a positive and negative voltage output, the point between two Zeners can act as the ground/return, with a positive and negative DC voltage at the other ends of the Zeners. This capability requires that there be no post-Zener rectification for the bottom/lower output.

Common ground, multiple outputs: Circuits using two or more output voltages can share a common ground point, but their total combined current draw must not exceed the rated current for the circuit (drawing too much will cause the output voltage to collapse). In this case, the Zeners would need to be selected such that they add to the desired voltages. For example, to generate 3V and 12V, a 3V Zener should be placed in series with a 9V Zener. As an added benefit for this scenario, if there is no post-Zener rectification for the 3V output, then the 3V output will be able to both sink and source current.

Zener Power Dissipation: As mentioned previously, Zener diodes may be connected in series to spread out power dissipation to overcome individual component power dissipation limits. Note that when this type of issue arises, it may become worthwhile to investigate using a standalone "wall wart" isolated power supply instead of a transformerless power supply. Even if the raw manufacturing cost of a transformerless supply is lower, an analysis of the steady-state power consumption of the transformerless power supply operating over the expected lifetime (e.g. plugged in continuously for 10 years) may show that electricity costs are higher that preferred. The transformerless power supply will consume constant average power, regardless of whether or not a load is connected.

Direct Driving TRIACs and SCRs

For transformerless power supplies used in conjunction with the control of TRIACs and SCRs, there is a key distinction between the full wave and half wave rectified circuits. For half wave rectification, one of the AC wires is directly connected to the ground of the low voltage DC output. This is contrasted with full wave rectification, where alternating diodes provide the conduction path to neutral, such that half the time, the DC ground is tied to AC neutral, and half the time it is tied to the AC line/hot.

Because there is no guaranteed tie-to-neutral for full wave rectification, the DC circuit must control TRIACs and SCRs through an isolation stage (such as an optotriac). This also means that the triggering of the TRIAC or SCR will be done by the AC voltage itself (through a gate current limiting resistor and the optotriac). This method of control works for half wave rectified circuits as well. However, it has the drawback that the control timing and gate current limiting


resistor must be designed with care to avoid overheating (e.g. by limiting triggering pulses to 50us or so typically). The gate must be turned on long enough for the device to latch on, but must be turned off soon enough that that resistor does not overheat after sustained operations. This is because the gate resistor has the full AC voltage across it for as long as the gate is held on.

For the half wave circuit, there exists another option: driving the TRIAC or SCR directly from low voltage DC logic. Because the DC ground is shared with the AC neutral, the low voltage DC circuitry can provide the gate trigger current needed to turn on the TRIAC or SCR. If the circuit can be powered with enough current from only a half-wave rectified solution, this will not only reduce cost (by avoiding an optotriac) but it can also simplify control and reduce heat generation. With the gate signal driven from a low voltage, the gate signal can be on indefinitely. This enables the use of a TRIAC or SCR in the same manner as a relay (continuous on/off signal) which can free up a microcontroller timer. It also reduces timing requirements for applications which elect to use phase-angle firing, as the turn off time for the gate signal does not need to be as precise as in the optotriac-driven gate signal.

neutral (which measures 0VAC with respect to the earth/safety ground contact) reduces some high voltage risk by keeping the potential of the low voltage DC near earth ground. Risk is reduced for both test/debug/development equipment and personnel.

Impedance and Rectification Placement

The Microchip Application Note AN954 shows transformerless power supplies in a distinctly different manner than the convention used in this DesignNote. Specifcally, AN954 shows the impedance and rectification components connected to the neutral AC wire rather than the line AC wire (hot). This may raise the question of whether it matters which approach is employed.
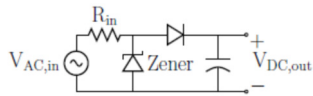
Impedance/Rectification on AC Line
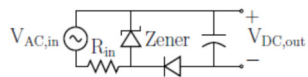
Impedance/Rectification on AC Neutral

For many applications, it does not necessarily matter whether components are placed on the line or neutral side, so both configurations are valid. However, there are application-specific considerations for half-wave rectified circuits which may benefit from placing all components on the line/hot side (as shown throughout this DesignNote) which have no drawbacks, so this practice is recommended in the absence of other extenuating circumstances. Benefits of placing the impedance on the hot/line side for half-wave rectified circuits include:

- *The ability to drive TRIACs and SCRs directly*, as mentioned previously
- *The circuit potential is kept near earth ground.* When developing the circuitry, using the