Introduction

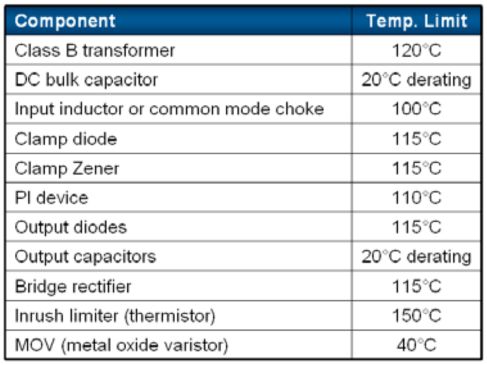
These course notes are to be read in association with the PI University video course, *Fixing a Flyback Supply That Has Overheating Components.*In this course, you will learn about the various causes behind overheating components in a switch mode power supply, and the steps for diagnosing and fixing the problems.

Before Starting This Course

Know your derating limits

Before starting this course, if your company or customer specifies derating limits on operating temperatures, you should know what these are for each major component on your board. If not, then refer to the manufacturer's datasheet for the maximum operating temperature of each component.

For your reference, a conservative list of operating temperature guidelines for each major component is shown here. These represent worst-case conditions, measured at highest ambient temperature and minimum and/or maximum line voltage. Component temperatures can be derated to meet specific safety requirements or to improve the lifetime of components. For example, the allowable operating temperatures of electrolytic capacitors are a function of the expected lifetime of the component. A 105°C, 2,000-hour rated capacitor operated continuously at 70°C will have an expected lifetime of about 20,000 hours.



Component	Temp. Limit
Class B transformer	120°C
DC bulk capacitor	20°C derating
Input inductor or common mode choke	100°C
Clamp diode	115°C
Clamp Zener	115°C
PI device	110°C
Output diodes	115°C
Output capacitors	20°C derating
Bridge rectifier	115°C
Inrush limiter (thermistor)	150°C
MOV (metal oxide varistor)	40°C

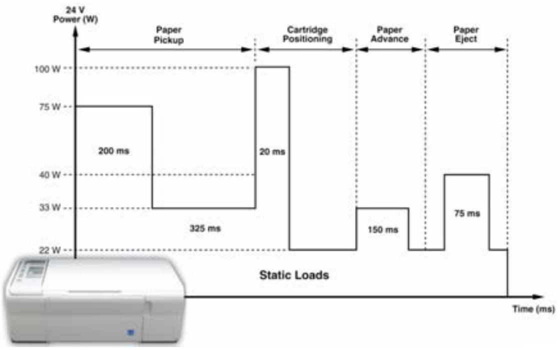
Conservative temperature limits

You should measure and determine which components are violating their maximum operating temperature while running at full load at both minimum and maximum line voltage.

Verify load characterization

Before continuing, first verify that your load is not drawing a higher power than is specified for your design.

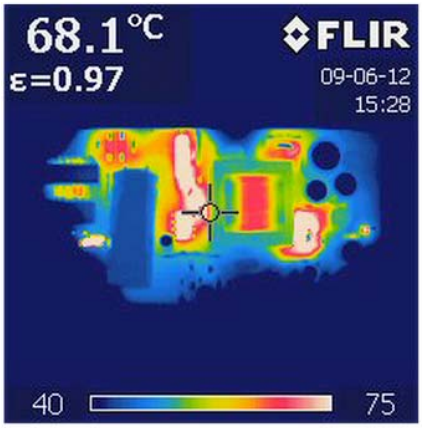
For example, the load characterization for an inkjet printer is shown here. Although the static load required by the printer is only 22 W, the average power when including transients is 31 W with peaks up to 100 W. If this printer was connected to a 22 W power supply, the supply would overheat during use.



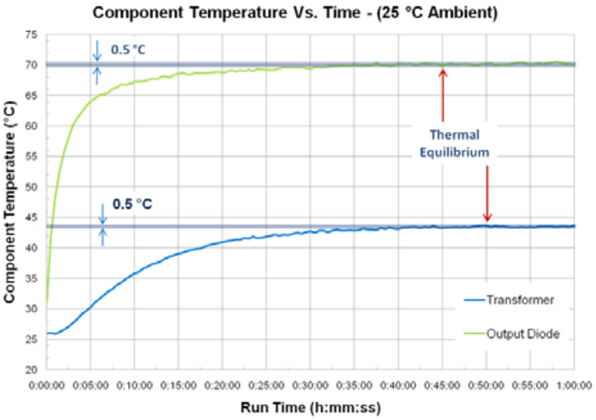
Inkjet printer load characterization

Confirm the load characterization by attaching an electronic load set to draw the total average output power you specified in *PI Expert*$^{(R)}$.

If the overheating problem goes away when testing with an electronic load, you should re-characterize your load and redesign your power supply in *PI Expert*.



Thermal view of components



Reaching thermal equilibrium

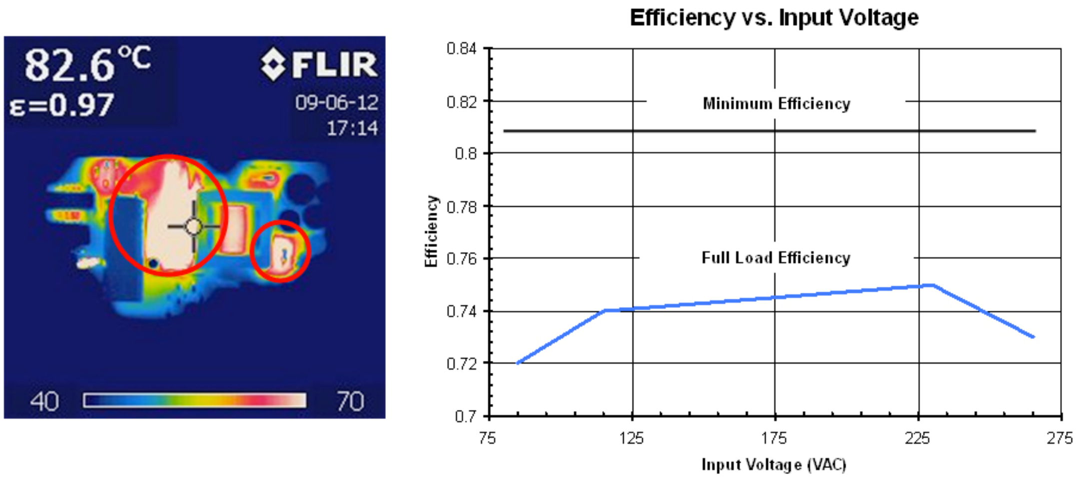
In cases where overheating is extremely obvious, such as a smoking resistor, it is not necessary to measure its temperature before resolving the issue. For all other measurements, allow sufficient time for the power supply to reach thermal equilibrium before taking your measurements. In some cases, this may take more than one hour. A good estimate of thermal equilibrium is the point where component temperatures change less than 0.5°C over a ten-minute period.

Overheating Analysis by Component Type

If any of the following components is overheating in your design, measure the efficiency of your power supply before continuing:

- Output diode
- Transformer
- Input inductor or common-mode choke
- Bridge rectifier
- Input capacitor
- Power Integrations device

If the efficiency is lower than the target entered in *PI Expert* by 5% or more, then losses are higher than expected in your circuit. Power lost in a flyback supply is converted to heat and can explain why some components are overheating. Resolve this issue before continuing.



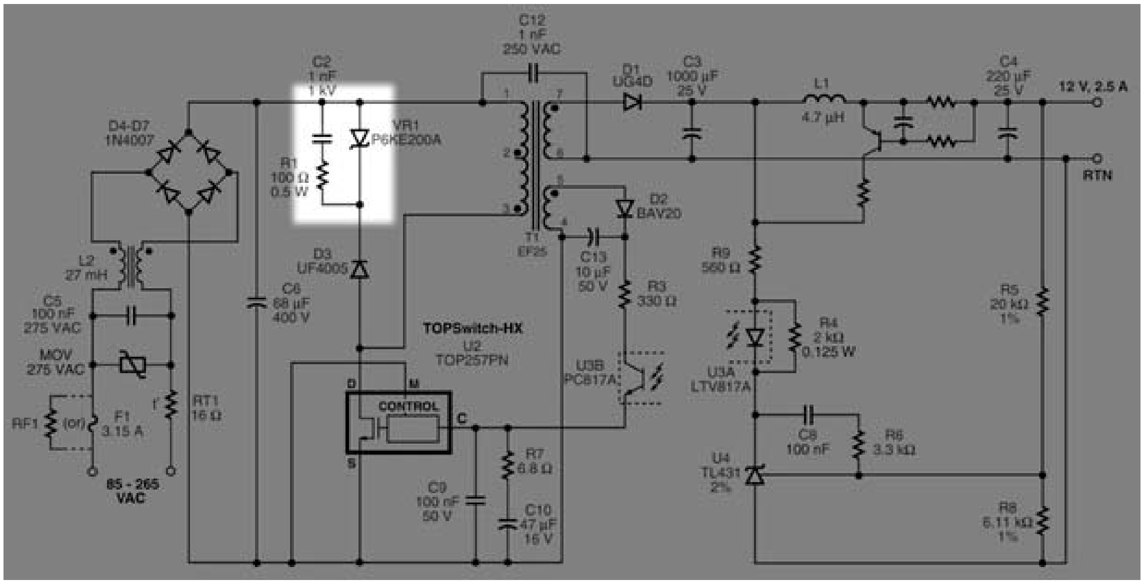
Power loss may cause overheating

Note: The equipment and procedures required to measure power supply efficiency can be found in the PI University Course Notes, *Techniques for Measuring Efficiency*.

If the measured efficiency matches within 5% of the target, please continue through this course to resolve the issue.

Overheating clamp

If your clamp is overheating, this can be indicative of design problems.



An overheating clamp can indicate serious design problems

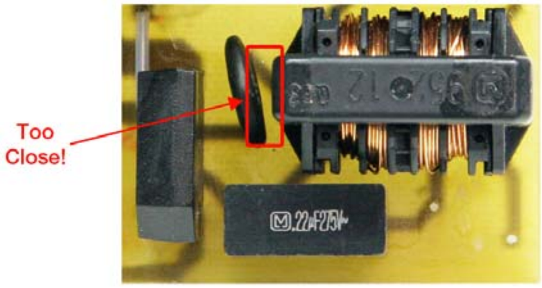
To diagnose this problem, you will need to confirm that all components in your clamp have been properly sized (see the Clamp Sizing Design Guide in Appendix A).

Overheating transformer

If your transformer is overheating, this can indicate other design problems. You will need to debug your transformer design to address this issue. Please contact your local Power Integrations technical support representative if you need assistance resolving this problem.

Overheating input inductor or common-mode choke

If the input common-mode choke is overheating, first verify that it is not located physically close to a component that runs at a very high temperature, such as a thermistor. If it is, you will need to re-layout your board to move the high-temperature component away from the common-mode choke.



Verify location of the common-mode choke

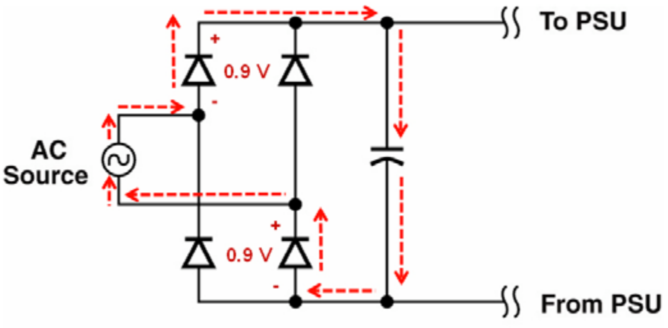
If the inductor itself is overheating, this indicates excessive power dissipation through the series resistance of the inductor winding. To reduce the power dissipation, replace it with an inductor rated for a higher current. This will increase the wire diameter and reduce its series resistance.

Overheating bridge rectifier

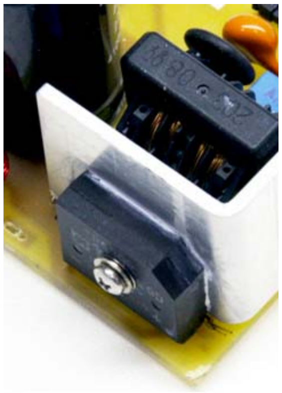
The power lost in a diode bridge rectifier is equal to the average input current multiplied by the worst-case forward drop of two diodes, which is about 1.8 volts. Selecting diodes with a larger current rating will reduce the resistive losses and lower component temperatures.

For designs with an output power more than approximately 30 to 40 W, it may be necessary to select a packaged bridge rectifier, which can be attached to a heatsink.

$$P_{diode} = [0.9\text{ V} + 0.9\text{ V}] \times I_{Avg\ Input\ Current}$$



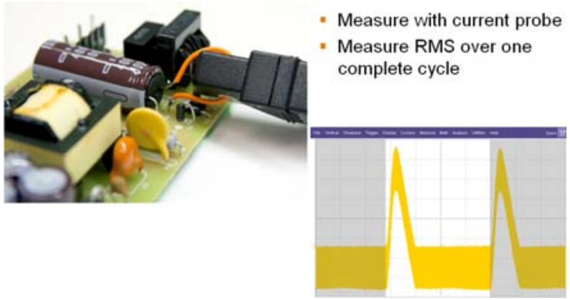
Power lost in a diode bridge rectifier



Attach packaged bridge rectifier to heatsink

Overheating input capacitor

The heat in an electrolytic capacitor is generated by ripple current flowing through its equivalent series resistance or ESR. If your design uses full-wave rectification, first check that none of the diodes in your bridge has failed. A diode that has failed open circuit will convert the bridge to a half-wave rectifier. This will significantly increase the ripple current through the input capacitor.



- Measure with current probe
- Measure RMS over one complete cycle

Using a current probe to measure RMS ripple current

Next, verify that the ripple current rating of your capacitor meets or exceeds the actual RMS ripple current flowing through the capacitor. The RMS ripple current into an input capacitor can be found in one of two ways. The first and most straightforward way is to insert a current loop between the capacitor and the board, and then measure the total RMS current flowing into and out of the capacitor using an oscilloscope and a current probe. Make sure to set the RMS and averaging time periods of your scope to measure one complete cycle.

Alternatively, the RMS ripple current can be approximated using the equation shown here.

$$I_{BRMS} = \sqrt{\left(\frac{I_{CHP}}{3} + \frac{1-D_S}{D_S} * I_{DCHAV}^2\right) * \frac{T_C}{T_B} + \frac{I_{DCHAV}^2}{D_S} * \frac{T_B - T_C}{T_B}}$$

$$V_{BV} = VMIN \rightarrow PIExpert$$

$$T_B = \frac{1}{2} * \frac{1}{f_L}$$

$$V_{BP} = \sqrt{2} * VACMIN \rightarrow PIExpert$$

$$V_{BAVG} = V_{BV} + (V_{BP} - V_{BV}) * \frac{1}{2}$$

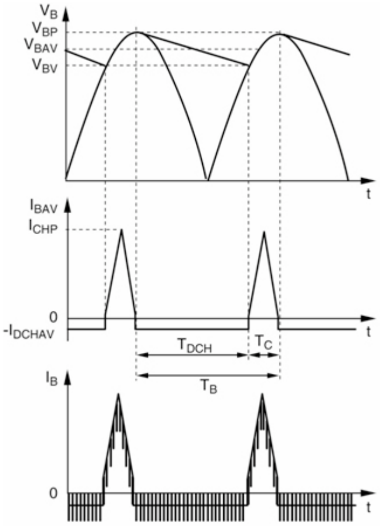
$$T_C \rightarrow PIExpert$$

$$I_{CHP} = 2 * C_{IN1} * \frac{V_{BP} - V_{BV}}{T_C}$$

$$VOR \rightarrow PIExpert$$

$$I_{DCHAV} = \frac{T_C}{T_B - T_C} * \frac{I_{CHP}}{2}$$

$$D_S = \frac{VOR}{V_{BAVG} + VOR}$$



Huber, Laszlo and Jovanovic, Milan M. "Evaluation of Flyback Topologies for Notebook AC/DC Adapter/Charger Applications." (www.deltartp.com)

Calculate primary capacitor ripple current

In this equation:

- T_B is the total time of one capacitor charge/discharge cycle, which is equal to one half of the line voltage period for full-wave rectified designs
- V_{BV} is the lowest voltage seen on the DC bus and is equal to the value VMIN calculated by *PI Expert* for the specified input capacitor value
- V_{BP} is the peak voltage seen on the DC bus and is equal to the VACMIN specified in *PI Expert* times √2
- T_C is the conduction time for the diode bridge rectifier, as specified in *PI Expert*
- I_{CHP} and I_{DCHAV} are the peak charging and average discharging currents of the bulk capacitor, respectively (both can be calculated by the equations given)
- D_S represents the duty cycle of the switching MOSFET

For a basic approximation, use the average duty cycle of the supply. Because the diode bridge conduction time is relatively small, you can assume that the average DC bus voltage is equal to VMIN plus one half the total voltage ripple. From here, you can calculate D average by rearranging the transfer function for a flyback supply.

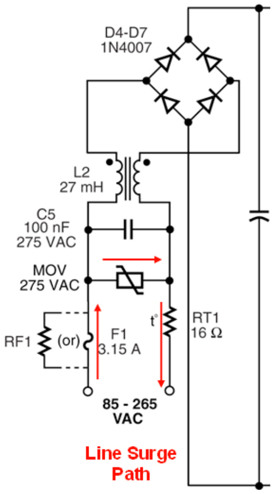
If the capacitor is rated correctly, then either increase the value of the capacitor or use two capacitors in parallel, both of which will lower the effective ESR. Alternatively, select a capacitor of the same value from a different series with a lower ESR. If you change the value of the input bulk capacitor, you should iterate your design in *PI Expert* with the new value.

Overheating metal oxide varistor

Metal oxide varistors (MOVs) are used to clamp differential line surges. If your design uses an MOV, verify that its voltage rating is above the maximum AC input line voltage. MOV voltages for universal input power supplies are typically 275 or 320 V.

Over many surge events, the MOV will degrade, reducing its voltage rating and resulting in increased dissipation. If the MOV has not been subjected to many line surges, it is possible that the component is defective.

In all cases, if the voltage rating is correct and the MOV is running hot, replace it with a new component.



MOV overheating caused by degradation

Overheating output capacitor

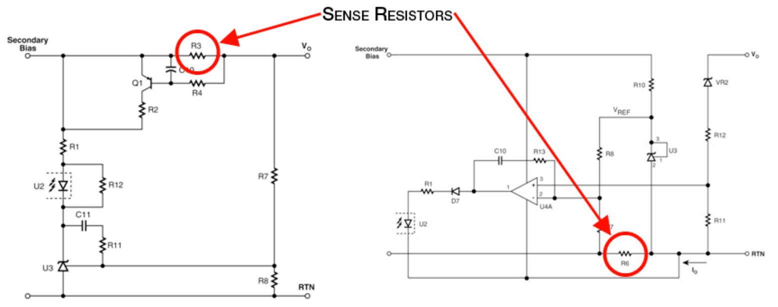
First, verify that the ripple current rating of your capacitor meets or exceeds the value specified by *PI Expert*. This can be found under the Design Results tab in the Output Capacitor RMS Ripple Current field. If the capacitor is rated correctly, then reduce its dissipation by selecting a capacitor with a lower ESR or by placing multiple capacitors in parallel to reduce the total ESR.

When using multiple output capacitors in parallel on a single output, verify that the PCB layout trace lengths to each capacitor are equal to ensure that the ripple current is equally shared between all capacitors. If the PCB layout trace lengths are not equal, one of the capacitors will run hotter than the rest, and you will need to re-layout your board.

Overheating output current sense

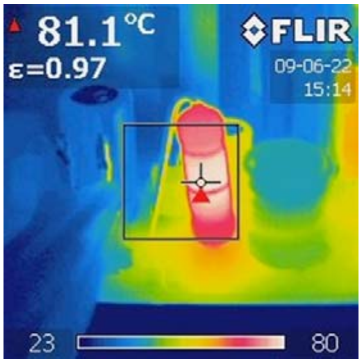
The power dissipated in an output current sense resistor is equal to V^2/R, where V is the sense voltage and R is the sense resistor value. The sense voltage is typically 0.3 to 0.7 V for transistor-based sensing or 50 to 100 mV for op-amp-based circuits.

If the resistor is not sufficiently oversized above the dissipated power, it will get extremely hot. The power rating of a resistor is typically specified for a surface temperature of 70°C. Operating a resistor above this temperature can significantly shorten its lifespan.



- Voltage drop = 0.7 V
- Voltage drop = 0.1 V

Sense voltage



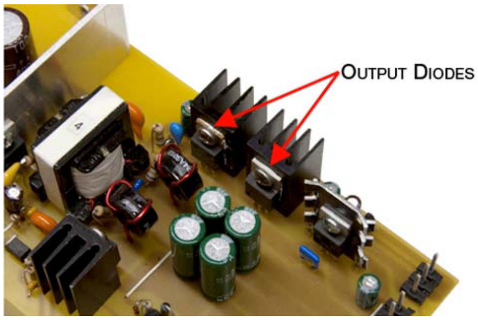
Resistor overheating

To reduce the resistor's temperature, consider mounting it vertically on the PCB, if you have not done so already. This will allow increased airflow around the resistor and increased lead length to help dissipate heat. Alternatively, consider using a resistor with a higher power rating.

The other solution is to decrease the amount of power dissipated in the resistor. There are two ways to reduce the power dissipated by a current sense resistor. Either divide the power between multiple resistors in parallel or, if using a transistor-based sensing circuit, reduce the voltage drop across the resistor by changing the circuit to an op-amp-based design.

Overheating output diode

Output diodes are typically one of the hottest components on the board, and it is normal to measure a 50°C rise above ambient, even with an external heatsink. If the output diode temperature is still too high, first confirm that the diode type and rating are correct, as specified by *PI Expert*.

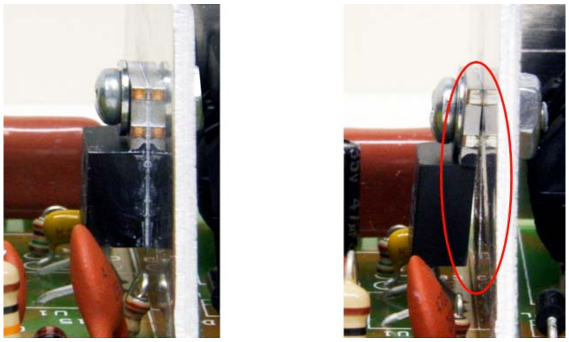


Overheating output diodes

Flyback converters should use only ultra-fast recovery or Schottky diodes as output rectifiers. Standard rectifier diodes should never be used. If a fast or ultra-fast recovery diode is overheating, and the peak inverse voltage across the diode is low enough to allow a Schottky type to be used, then replacing it with a similarly rated Schottky will reduce the temperature. The peak inverse voltage across your output diode can be found under the Design Results tab in *PI Expert*.

Adding another, similarly rated diode in parallel with your existing diode will also lower its temperature. Using a diode with a larger current rating, and therefore less resistance, may also provide some improvement.

If the diode is the correct size and type, then greater heatsinking must be used.



Ensure co-planarity

For TO-220 packaged diodes, using thermal compound or a thermal pad will decrease the thermal resistance between the case and heatsink. However, when using thermal grease, be careful to minimize the thickness of the layer. A thick layer will reduce heat transfer between the surfaces and increase the device temperature.

Also, ensure that the device is co-planar along the entire heatsink surface. Avoid over-torquing the mounting screw, as this may cause the package to separate from the heatsink.

If necessary, select a larger heatsink to reduce the temperature.

For axial diodes, you will need to increase the copper area on the PCB at the cathode pad of the diode. When using one-ounce copper-clad boards, increasing the copper depth to two ounces will also reduce the temperatures of axial diodes that use PCB heatsinking.

Overheating Power Integrations device

If the Power Integrations device is operating too hot or entering thermal shutdown, you should increase the amount of heatsinking in your design.

If using a DIP or surface-mount packaged device, re-layout your board to maximize the copper area of the source plane. This is the primary heatsinking mechanism of the device.

When using one-ounce copper-clad boards, increasing the copper depth to two ounces will reduce the temperatures of every component that uses PCB heatsinking, including the Power Integrations device. If you still cannot dissipate enough heat through the source plane on the board, then consider either switching to a package type that allows for external heatsinking or select the next larger Power Integrations device. The lower R_{dson} will reduce conduction losses and lower the device temperature.

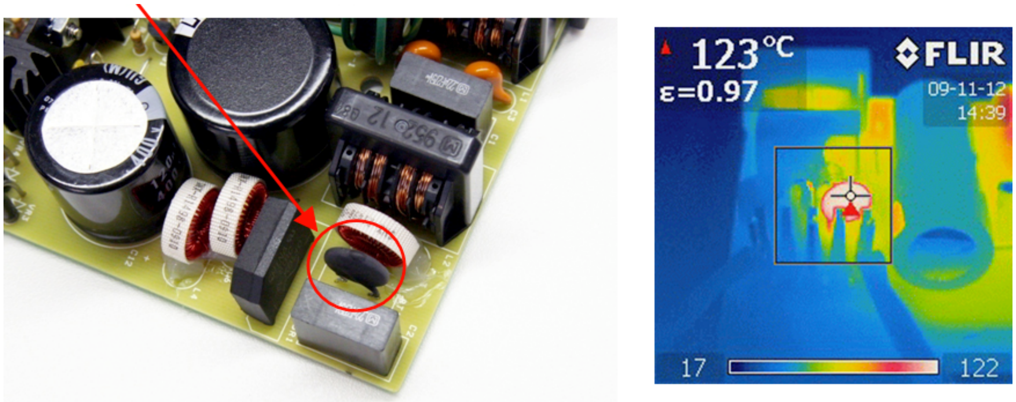
Note that some Power Integrations device families allow the internal current limit to be programmed so that a larger device can be used without redesigning your board.

When attaching a Power Integrations device to an external heatsink, use thermal grease to decrease the thermal resistance between the case and heatsink, but be careful to minimize the thickness of the layer. A thick layer will reduce heat transfer between the surfaces and increase the device temperature.

Also, ensure that the device is co-planar along the entire heatsink surface. Avoid over-torquing the mounting screw, as this may cause the package to separate from the heatsink.

Overheating thermistor

Input inrush thermistors are designed to run hot. It is common to measure a 100°C rise above ambient during normal operation. The resistance of thermistors decreases with increasing temperature, presenting a high impedance when cold to limit inrush current and decreasing rapidly as they heat up to prevent excessive dissipation.


Thermistor = $T_{ambient} + 100°C$

Overheating thermistor

Make sure the thermistor current rating matches the Average Diode Bridge Current found under the Design Results tab in *PI Expert*.

Overheating input fusible resistor

Because fusible resistors are dissipative, they should only be used in designs with an output power below approximately 10 W. If your design delivers more power than this, replace the fusible resistor with a fuse. If your design is less than 10 W, verify that the value of the fusible resistor fitted on your board matches that specified by your design.

Simply reducing the value of the resistor to lower its dissipation and temperature is not recommended. This can lead to catastrophic failure due to the higher inrush current when AC is first applied.

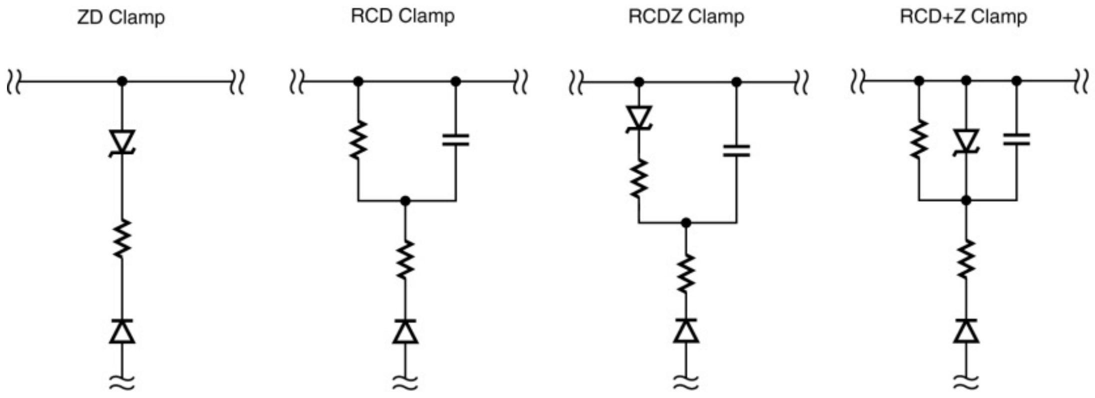
For More Information

If you have any questions or comments about the information presented in this course, please email PIUniversity@powerint.com.

Appendix A
Clamp Sizing Design Guide

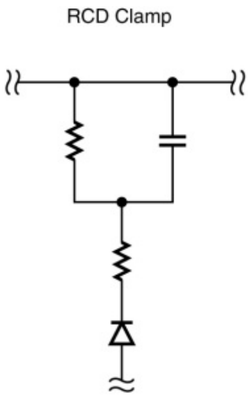
Introduction

This document provides a step-by-step procedure for sizing components in each of the four major clamp type circuits for a flyback power supply designed using *PI Expert*(R). Any assumptions made or approximations used have been noted, where appropriate. Note that a clamp design created by *PI Expert* may be slightly more conservative than one generated by the algorithm provided here. After an initial design of your clamp circuit, you should construct a prototype and verify its performance in your supply. If the results are significantly different than expected, reiterate the design.



The Four Clamp Types

Sizing an RCD Clamp



1. Measure the primary leakage inductance of your transformer, L_L
2. Check the switching frequency of your design used in *PI Expert*, f_s
3. Determine the correct primary current, I_P, as follows:
   (Note: All values found in *PI Expert*)
   - a. If your design uses power limit programming, $I_P = I_{LIMITEXT}$
   - b. If your design uses external current limit programming, $I_P = I_{LIMITEXT}$
   - c. For all other designs, $I_P = I_{LIMITMAX}$
4. Determine the total voltage allowed across the primary MOSFET and calculate $V_{maxclamp}$ as:
   $$V_{MOSFETmax} = (VAC_{HighLine} * \sqrt{2}) + V_{maxclamp}$$
   (Note: It is recommended that at least a 50 V margin be maintained below BVDSS for a MOSFET, with an additional 30 to 50 V margin to account for transient voltages. For universal input designs, it is recommended that $V_{maxclamp} < 200$ V. $V_{maxclamp}$ should never be less than approximately 1.5*VOR.)
5. Determine the voltage ripple across the clamp circuit, V_{delta}
   (Note: Typical value of 10% of $V_{maxclamp}$ recommended.)
6. Calculate the minimum voltage across the clamp circuit as:
   $$V_{minclamp} = V_{maxclamp} - V_{delta}$$

7. Calculate the average voltage across the clamp circuit, V_{clamp} as:

$$V_{clamp} = V_{maxclamp} - \frac{V_{delta}}{2}$$

8. Calculate energy stored in leakage reactance as:

$$E_{LL} = \frac{1}{2} * L_L * I_P^2$$

(Note: Not all leakage reactance energy is transferred to the clamp. As a result, the true energy dissipated by the clamp should be calculated using the above equation and substituting the peak primary current, I_P, with the current that only flows in the clamp: I_C. Because I_C is difficult to calculate or measure, we will adjust E_{LL} by a known scale factor to estimate the energy dissipated in the clamp: E_{clamp}.)

9. Estimate energy dissipated in the clamp, E_{clamp}, as:

$1.5\ W \leq P_{out} \leq 50\ W$ — $E_{clamp} = 0.8 * E_{LL}$

$50\ W < P_{out} \leq 90\ W$ — $E_{clamp} = E_{LL}$

$90\ W < P_{out}$ — $E_{clamp} = E_{LL} * \left(\frac{V_{clamp}}{V_{clamp} - VOR}\right)$

(Note: Clamp circuits are not typically required in power supplies with a continuous output power < 1.5 W.)

10. Calculate the clamp resistor value as:

$$R_{clamp} = \frac{V_{clamp}^2}{E_{clamp} * f_S}$$

(Note: The R_{clamp} value calculated here is a first approximation. After the power supply has been built, measure the average voltage V_{clamp} and compare it with the value used here. If the measured value is lower than expected, increase the value of R_{clamp} until the measured value matches these calculations. If the measured value is higher than expected, decrease the value of R_{clamp}.)

11. The clamp resistor power rating should be more than:

$$\frac{V_{clamp}^2}{R_{clamp}}$$

12. Calculate the clamp capacitor value as:

$$C_{clamp} = \frac{E_{clamp}}{\frac{1}{2} * [V_{maxclamp}^2 - V_{minclamp}^2]}$$

13. The clamp capacitor voltage rating should be more than: $1.5 * V_{maxclamp}$

14. A fast or ultra-fast recovery diode should be used as the blocking diode in a clamp circuit.

(Note: Under some circumstances, the use of a standard recovery diode may provide some improvement in efficiency and EMI. The standard recovery diode used for such a purpose **must** have a specified reverse recovery time listed. Careful attention should be paid to the reverse recovery current in this diode to ensure it is below acceptable limits. The approval of a standard recovery diode based design is not recommended without thorough evaluation.)

15. The PIV of the blocking diode should be more than: $1.5 * V_{maxclamp}$

16. The forward peak repetitive current rating of the blocking diode should be more than: I_P
If this parameter is not listed in the datasheet, the average forward current rating should be more than: $0.5 * I_P$
(Note: The average forward current rating of the diode may be specified lower, and is primarily constrained by thermal performance. The temperature of the blocking diode should be measured during steady-state operation at lowest input voltage to determine if the rating is appropriate. Heatsinking, component orientation, and final product enclosure all affect the operating temperate of the diode.)

17. Size the damping resistor (if used) as:

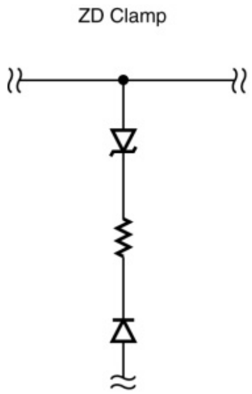
$$\frac{20}{0.8 * I_p}\ \Omega \leq R_{damp} \leq 100\ \Omega$$

(Note: For systems with a maximum continuous output power of 20 W or more, R_{damp} should only be used if absolutely necessary and should be restricted to a very small value: $1\ \Omega \leq R_{damp} \leq 4.7\ \Omega$.)

18. The damping resistor power rating should be more than:

$$I_p^2 * R_{damp}$$

Sizing a ZD Clamp



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    c. For all other designs, $I_P = I_{LIMITMAX}$
4. Determine the total voltage allowed across the primary MOSFET and calculate $V_{maxclamp}$ as:

$$V_{maxclamp} \text{ as: } V_{MOSFETmax} = (VAC_{HighLine} * \sqrt{2}) + V_{maxclamp}$$

(Note: It is recommended that at least a 50 V margin be maintained below BVDSS for a MOSFET, with an additional 30 to 50 V margin to account for transient voltages. For universal input designs, it is recommended that $V_{maxclamp} < 200$ V. $V_{maxclamp}$ should never be less than approximately 1.5*VOR.)

5. Calculate energy stored in leakage reactance as:

$$E_{LL} = \frac{1}{2} * L_L * I_P^2$$

(Note: Not all leakage reactance energy is transferred to the clamp. As a result, the true energy dissipated by the clamp should be calculated using the above equation and substituting the peak primary current, I_P, with the current that only flows in the clamp: I_C. Because I_C is difficult to calculate or measure, we will adjust E_{LL} by a known scale factor to estimate the energy dissipated in the clamp: E_{clamp}.)

6. Estimate energy dissipated in the clamp, E_{clamp}, as:

$1.5\ W \leq P_{out} \leq 50\ W$	$E_{clamp} = 0.8 * E_{LL}$
$50\ W < P_{out} \leq 90\ W$	$E_{clamp} = E_{LL}$
$90\ W < P_{out}$	$E_{clamp} = E_{LL} * \left(\frac{V_{clamp}}{V_{clamp} - VOR}\right)$

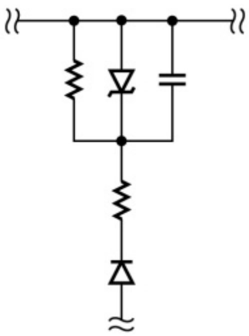
(Note: Clamp circuits are not typically required in power supplies with a continuous output power < 1.5 W.)

7. The TVS breakdown voltage is specified as: $V_{maxclamp}$
(Note: Round up, when necessary. A TVS must be used because a Zener diode cannot withstand the instantaneous peak power dissipated in the device.)
8. The TVS power rating should be at least $1.5 * E_{clamp} * f_s$
(Note: Use multiple TVS components in parallel to achieve power derating, if necessary. Verify that the TVS power rating is correct by measuring its temperature while the supply is running at full load and lowest input voltage. The body of a TVS should never exceed 70°C when operated at a 25°C ambient temperature. If your TVS is hotter than this, use a component rated for higher power or use multiple TVS components in parallel.)

9. A fast or ultra-fast recovery diode should be used as the blocking diode in a clamp circuit.
   (Note: Under some circumstances, the use of a standard recovery diode may provide some improvement in efficiency and EMI. The standard recovery diode used for such a purpose **must** have a specified reverse recovery time listed. Careful attention should be paid to the reverse recovery current in this diode to ensure it is below acceptable limits. The approval of a standard recovery diode based design is not recommended without thorough evaluation.)
10. The PIV of the blocking diode should be more than: $1.5*V_{maxclamp}$
11. The forward peak repetitive current rating of the blocking diode should be more than: I_P
    If this parameter is not listed in the datasheet, the average forward current rating should be more than: $0.5*I_P$
    (Note: The average forward current rating of the diode may be specified lower, and is primarily constrained by thermal performance. The temperature of the blocking diode should be measured during steady-state operation at lowest input voltage to determine if the rating is appropriate. Heatsinking, component orientation, and final product enclosure all affect the operating temperate of the diode.)
12. Size the damping resistor (if used) as:
    $$\frac{20}{0.8*I_p}\ \Omega \le R_{damp} \le 100\ \Omega$$
    (Note: For systems with a maximum continuous output power of 20 W or more, R_{damp} should only be used if absolutely necessary and should be restricted to a very small value: $1\ \Omega \le R_{damp} \le 4.7\ \Omega$.)
13. The damping resistor power rating should be more than:
    $$I_p^2 * R_{damp}$$

Sizing an RCD+Z Clamp

RCD+Z Clamp



1. Measure the primary leakage inductance of your transformer, L_L
2. Check the switching frequency of your design used in *PI Expert*, f_s
3. Check the peak primary current predicted by *PI Expert*, I_P
4. Determine the total voltage allowed across the primary MOSFET and calculate $V_{maxclamp}$ as:
   $$V_{MOSFETmax} = (VAC_{HighLine} * \sqrt{2}) + V_{maxclamp}$$
   (Note: It is recommended that at least a 50 V margin be maintained below BVDSS for a MOSFET, with an additional 30 to 50 V margin to account for transient voltages. For universal input designs, it is recommended that $V_{maxclamp} < 200$ V. $V_{maxclamp}$ should never be less than approximately 1.5*VOR.)
5. Determine the voltage ripple across the clamp circuit, V_{delta}
   (Note: typical value of 10% of Vmaxclamp recommended)
6. Calculate the minimum voltage across the clamp circuit as:
   $$V_{minclamp} = V_{maxclamp} - V_{delta}$$
7. Calculate the average voltage across the clamp circuit, V_{clamp} as:
   $$V_{clamp} = V_{maxclamp} - \frac{V_{delta}}{2}$$
8. Calculate energy stored in leakage reactance as:
   $$E_{LL} = \frac{1}{2} * L_L * I_P^2$$
   (Note: Not all leakage reactance energy is transferred to the clamp. As a result, the true energy dissipated by the clamp should be calculated using the above equation and substituting the peak primary current, I_P, with the current that only flows in the clamp: I_C. Because I_C is difficult to calculate or measure, we will adjust E_{LL} by a known scale factor to estimate the energy dissipated in the clamp: E_{clamp}.)

9. Estimate energy dissipated in the clamp, E_{clamp}, as:

$1.5\,W \le P_{out} \le 50\,W$	$E_{clamp} = 0.8 * E_{LL}$
$50\,W < P_{out} \le 90\,W$	$E_{clamp} = E_{LL}$
$90\,W < P_{out}$	$E_{clamp} = E_{LL} * \left(\frac{V_{clamp}}{V_{clamp} - VOR}\right)$

(Note: Clamp circuits are not typically required in power supplies with a continuous output power < 1.5 W.)

10. Calculate the clamp resistor value as:

$$R_{clamp} = \frac{V_{clamp}^2}{E_{clamp} * f_S}$$

(Note: The R_{clamp} value calculated here is a first approximation. After the power supply has been built, measure the average voltage V_{clamp} and compare it with the value used here. If the value you measure is lower than expected, increase the value of R_{clamp} until the measured value matches these calculations. If the measured value is higher than expected, decrease the value of R_{clamp}.)

11. The clamp resistor power rating should be more than:

$$\frac{V_{clamp}^2}{R_{clamp}}$$

12. Calculate the clamp capacitor value as:

$$C_{clamp} = \frac{E_{clamp}}{\frac{1}{2} * [V_{maxclamp}^2 - V_{minclamp}^2]}$$

13. The clamp capacitor voltage rating should be more than: $1.5 * V_{maxclamp}$

14. Specify the TVS breakdown voltage as approximately: $V_Z = V_{maxclamp} + 20\text{ V}$
(Note: A TVS must be used because a Zener diode cannot withstand the instantaneous peak power seen across the device at turn on.)

15. The TVS power rating should be sized to handle the difference in energy stored during normal operation and overload:

$$P_{TVS} > \frac{1}{2} * L_L * [I_{LIMITMAX}^2 - I_P^2] * f_S$$

(Note: All current limit values found in *PI Expert*.)

16. A fast or ultra-fast recovery diode should be used as the blocking diode in a clamp circuit.
(Note: Under some circumstances, the use of a standard recovery diode may provide some improvement in efficiency and EMI. The standard recovery diode used for such a purpose **must** have a specified reverse recovery time listed. Careful attention should be paid to the reverse recovery current in this diode to ensure it is below acceptable limits. The approval of a standard recovery diode based design is not recommended without thorough evaluation.)

17. The PIV of the blocking diode should be more than: $1.5 * V_{maxclamp}$

18. The forward peak repetitive current rating of the blocking diode should be more than: I_P
If this parameter is not listed in the datasheet, the average forward current rating should be more than: $0.5 * I_P$
(Note: The average forward current rating of the diode may be specified lower, and is primarily constrained by thermal performance. The temperature of the blocking diode should be measured during steady-state operation at lowest input voltage to determine if the rating is appropriate. Heatsinking, component orientation, and final product enclosure all affect the operating temperate of the diode.)

19. Size the damping resistor (if used) as:

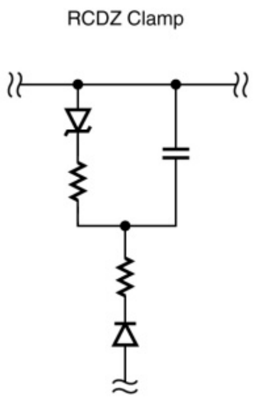
$$\frac{20}{0.8 * I_p}\,\Omega \le R_{damp} \le 100\,\Omega$$

(Note: For systems with a maximum continuous output power for 20 W or more, R_{damp} should only be used if absolutely necessary and should be restricted to a very small value: $1\,\Omega \le R_{damp} \le 4.7\,\Omega$.)

20. The damping resistor power rating should be more than:

$$I_p^2 * R_{damp}$$

Sizing an RCDZ Clamp



RCDZ Clamp

1. Measure the primary leakage inductance of your transformer, L_L
2. Check the switching frequency of your design used in *PI Expert*, f_s
3. Determine the correct primary current, I_P, as follows:
   (Note: All values found in *PI Expert*.)
   a. If your design uses power limit programming, $I_P = I_{LIMITEXT}$
   b. If your design uses external current limit programming, $I_P = I_{LIMITEXT}$
   c. For all other designs, $I_P = I_{LIMITMAX}$
4. Determine the total voltage allowed across the primary MOSFET and calculate $V_{maxclamp}$ as:

$$V_{MOSFETmax} = (VAC_{HighLine} * \sqrt{2}) + V_{maxclamp}$$

   (Note: It is recommended that at least a 50 V margin be maintained below BVDSS for a MOSFET, with an additional 30 to 50 V margin to account for transient voltages. For universal input designs, it is recommended that $V_{maxclamp} < 200$ V. $V_{maxclamp}$ should never be less than approximately 1.5*VOR.)
5. Determine the voltage ripple across the clamp circuit, V_{delta}
   (Note: Typical value of 10% of $V_{maxclamp}$ recommended.)
6. Calculate the minimum voltage across the clamp circuit as:

$$V_{minclamp} = V_{maxclamp} - V_{delta}$$

7. Calculate the average voltage across the clamp circuit, V_{clamp} as:

$$V_{clamp} = V_{maxclamp} - \frac{V_{delta}}{2}$$

8. Calculate energy stored in leakage reactance as:

$$E_{LL} = \frac{1}{2} * L_L * I_P^2$$

   (Note: Not all leakage reactance energy is transferred to the clamp. As a result, the true energy dissipated by the clamp should be calculated using the above equation and substituting the peak primary current, I_P, with the current that only flows in the clamp: I_C. Because I_C is difficult to calculate or measure, we will adjust E_{LL} by a known scale factor to estimate the energy dissipated in the clamp: E_{clamp}.)
9. Estimate energy dissipated in the clamp, E_{clamp}, as:

$$\begin{aligned} &1.5\,W \le P_{out} \le 50\,W && E_{clamp} = 0.8 * E_{LL} \\ &50\,W < P_{out} \le 90\,W && E_{clamp} = E_{LL} \\ &90\,W < P_{out} && E_{clamp} = E_{LL} * \left(\frac{V_{clamp}}{V_{clamp} - VOR}\right) \end{aligned}$$

   (Note: Clamp circuits are not typically required in power supplies with a continuous output power < 1.5 W.)
10. The Zener breakdown voltage is specified as: $V_Z \ge VOR$
    (Note: Round up, when necessary. V_Z should never be specified as less than VOR.)
11. Calculate the clamp resistor value as:

$$R_{clamp} = \frac{[V_{clamp} - V_Z]^2}{E_{clamp} * f_S}$$

12. Calculate the power rating of the clamp resistor as:

    $$1.5 * \frac{[V_{clamp}-V_Z]^2}{R_{clamp}}$$

    (Note: The R_{clamp} value calculated here is a first approximation. After the power supply has been built, measure the average voltage V_{clamp} and compare it with the value used here. If the value you measure is lower than expected, increase the value of R_{clamp} until the measured value matches these calculations. If the measured value is higher than expected, decrease the value of R_{clamp}.)
13. The Zener power rating should be specified as more than:

    $$1.5 * V_Z * \left[\frac{E_{clamp}*f_S}{V_{clamp}}\right]$$

    (Note: Use multiple Zeners in parallel to achieve power derating, if necessary. If the power rating is too large for a Zener diode, a TVS may be used instead. Verify that the Zener power rating is correct by measuring its temperature while the supply is running at full load and lowest input voltage. The body of a Zener should never exceed 70°C when operated at a 25°C ambient temperature.)
14. Calculate the clamp capacitor value as:

    $$C_{clamp} = \frac{E_{clamp}}{\frac{1}{2} * [V_{maxclamp}^2 - V_{minclamp}^2]}$$
15. The clamp capacitor voltage rating should be more than: $1.5*V_{maxclamp}$
16. A fast or ultra-fast recovery diode should be used as the blocking diode in a clamp circuit.
    (Note: Under some circumstances, the use of a standard recovery diode may provide some improvement in efficiency and EMI. The standard recovery diode used for such a purpose **must** have a specified reverse recovery time listed. Careful attention should be paid to the reverse recovery current in this diode to ensure it is below acceptable limits. The approval of a standard recovery diode based design is not recommended without thorough evaluation.)
17. The PIV of the blocking diode should be more than: $1.5*V_{maxclamp}$
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    If this parameter is not listed in the datasheet, the average forward current rating should be more than: $0.5*I_P$
    (Note: The average forward current rating of the diode may be specified lower, and is primarily constrained by thermal performance. The temperature of the blocking diode should be measured during steady-state operation at lowest input voltage to determine if the rating is appropriate. Heatsinking, component orientation, and final product enclosure all affect the operating temperate of the diode.)
19. Size the damping resistor (if used) as:

    $$\frac{20}{0.8*I_p}\,\Omega \le R_{damp} \le 100\,\Omega$$

    (Note: For systems with a maximum continuous output power for 20 W or more, R_{damp} should only be used if absolutely necessary and should be restricted to a very small value: $1\,\Omega \le R_{damp} \le 4.7\,\Omega$.)
20. The damping resistor power rating should be more than:

    $$I_p^2 * R_{damp}$$

For More Information

If you have any questions about the information presented in this document, please post your inquiry on the PI Power Supply Design Forum.