Application Note 27

Troubleshooting Switching Power Supplies

by Jeff Dixon

Overview

This application note provides insight on troubleshooting and taking measurements in switching power supplies. Specific measurements include output ripple, line and load regulation, efficiency, and transient response. Troubleshooting and measurement of flyback and forward converter transformers are also covered.

Common measurement mistakes are also demonstrated, including using uncompensated scope probes. The final topic is an in-depth example of troubleshooting an off-line flyback power supply. Off-line flyback topologies involve all dc-dc converter circuit blocks, plus the ac front end, thus cover most troubleshooting problems.

Output Ripple Measurement

Output ripple is a very common measurement but is also the most likely to be incorrectly performed. To perform a "sanity check," it is important to know what to expect, why ripple is present, and where output ripple comes from.

What to Expect

Typically switching power supplies have 100mV to 200mV of output ripple without a second-stage filter.

Why Ripple is Present

Ripple is present because of the charging and discharging of current through the output inductor.

Where Ripple Comes From

Ripple is mostly a function of the output capacitor's ESR and the current flowing through the output inductor. (Figure 1) shows the trapezoidal current flowing through the inductor that creates an I·R drop across the ESR of the output capacitor that creates the output ripple.

Output Ripple Example

The output capacitor has an ESR of 100mΩ, and the peak-to-peak current through the output inductor is 0.25A. Figures 2 and 3 show examples of the inductor current waveform and the resulting output voltage ripple waveforms respectively.

The output ripple is:

$$V_{RIPPLE} = ESR \times \Delta I_L$$

(1) $$V_{RIPPLE} = 0.10\Omega \times 0.25\,A = 25mV_{PP}$$

Hint

The output ripple, or output noise, should be measured using an oscilloscope. Avoid using a meter since most meters are only accurate with sine waves, and switching power supplies usually have a nonsinusoidal waveform. If a meter must be used, use a true RMS meter with a bandwidth at least twice the frequency of the signal being measured.

Output Ripple Measurement

Procedure

Example using an MIC4575 switching regulator:

1. Connect the test circuit as shown in Figure 4.
2. Double check connections.
3. Current limit the bench-top supply to a safe level (2A in this example).
4. Apply power.
5. Apply the 100% load (3.3V/1A = 3.3Ω) as shown in Figure 4.
6. Modify scope probe as shown in Figure 3b.
7. Place the modified scope probe on the output of the supply.
8. Adjust the horizontal sweep time to show three repetitive waveforms and:
   – set the oscilloscope to ac coupling
   – set the vertical sweep (amplitude) so the waveform displaces two to three divisions.
9. Use Figure 3a as a reference for an output voltage ripple waveform.

Results

Figure 2a shows what the output ripple looks like with an unmodified scope probe.

Figure 2b is an example of the ripple being measured incorrectly with an unmodified scope probe setup.

Figure 3a shows the output ripple when using a modified scope probe.

Figure 3b demonstrates how the modified scope probe is used when actually making a measurement.

Figure 3c shows the scope probe disassembled before the handmade copper ground lead is wrapped around the ground shield. Notice that the probe has been partially disassembled to expose the oscilloscope's ground shield. A modified ground lead was created by carefully wrapping a piece of *malleable* copper wire around the probe's exposed ground shield. A short ground lead is important because it behaves like an antenna and picks up RFI (radio frequency interference) typical of a switching power supply. The proof is in the pictures. Figure 3a was measured correctly and had only 26mV of output ripple versus Figure 2a with over 47mV of output ripple. Note the above procedure does not guarantee a correct reading if the probe is out of calibration or the probe is not modified correctly.

Load Regulation

Load regulation is the variation in power supply output voltage from no load to full load. The result is expressed as a percentage of the output voltage over a load variation.

$$\text{(2)} \quad \%\,\text{Regulation} = \frac{V_{OUT(no\ load)} - V_{OUT(full\ load)}}{V_{OUT(full\ load)}} \times 100$$

Smaller load regulation percentages are better. When the load suddenly changes from 100% to 0% of the rated output current, the output voltage will change by some small percentage of full load voltage.

To measure load regulation:

- Connect the circuit as shown in Figure 4.
- Let position 2 represent no load; let position 3 represent the full load after adjusting R2.
- Apply power to the DUT (device under test). In this case, an MIC4575BU 200kHz buck regulator.
- Measure the output voltage with switch set for no load and again with full load applied.
- Using the formula provided in Equation 2, calculate load regulation.

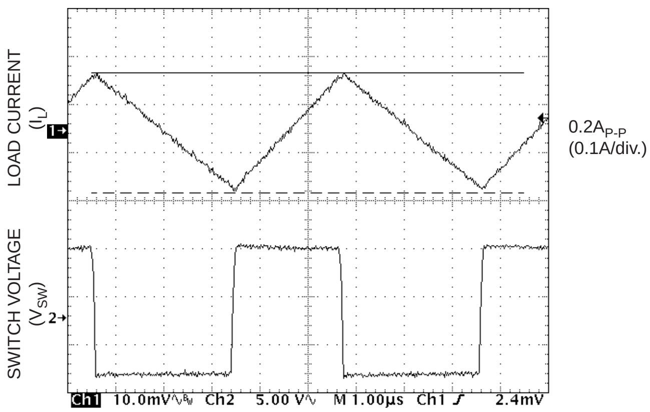


Figure 1. Inductor Current Trapezoid

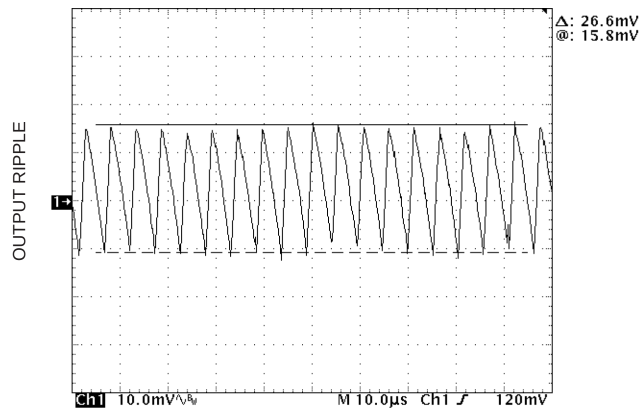


Figure 3a. Output Ripple, Modified Probe

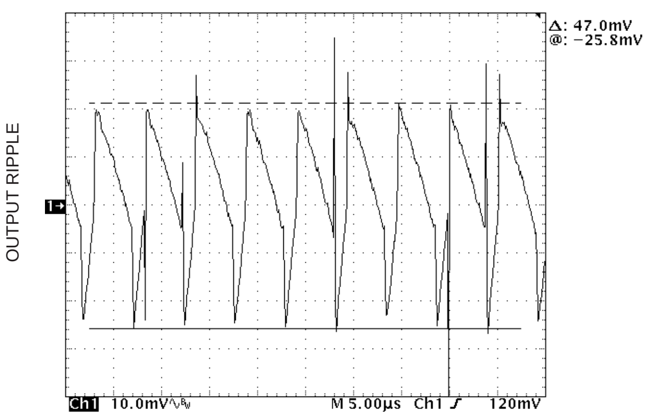


Figure 2a. Output Ripple, Unmodified Probe

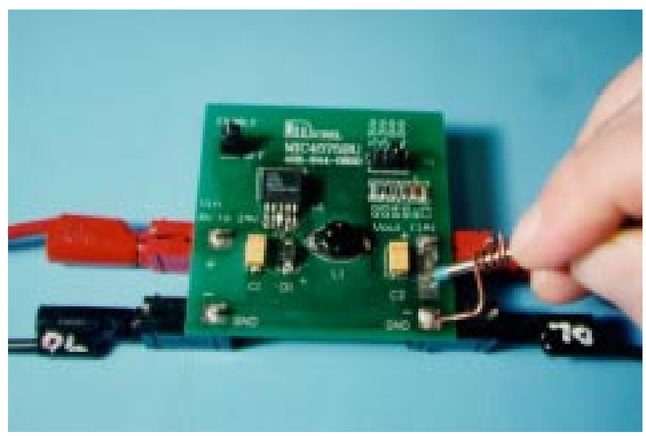


Figure 3b. Measuring with a Modified Probe

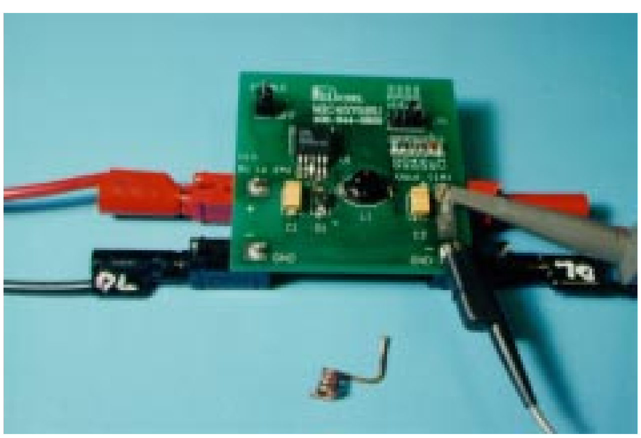


Figure 2b. Measuring with an Unmodified Probe

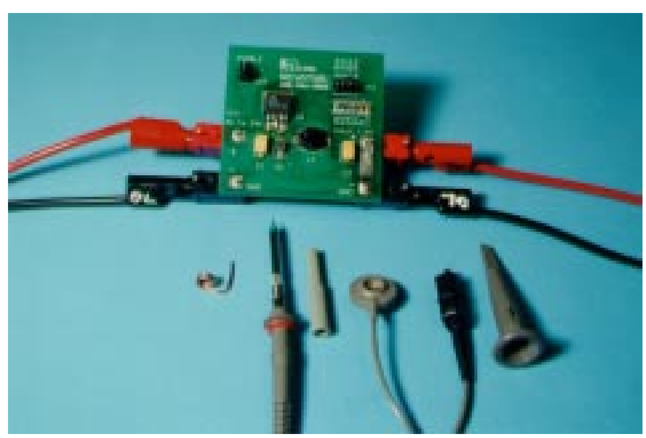
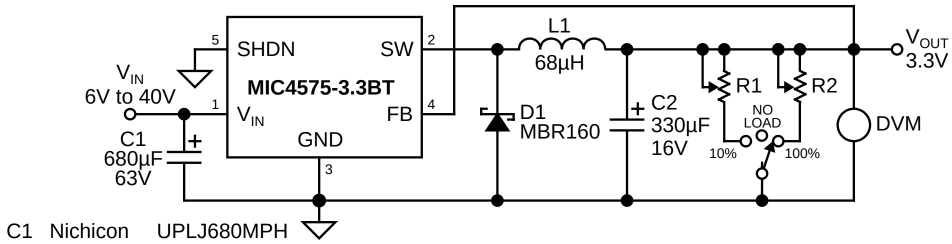


Figure 3c. Modified Probe (Disassembled)



C1	Nichicon	UPLJ680MPH
C2	Nichicon	UPL1C33MPH
D1	Motorola	MBR160
L1	Sumida	RCH106-680K

Adjust R1 to 33Ω for 100mA output (10% load).
Adjust R2 to 3.3Ω for 1A output (100% load).
Set switch to NO LOAD if specificaion requires a no load condition.

Figure 4. Line and Load Regulation Test Schematic

If, for example, the measurements are 3.30V for no load and 3.25V with full load applied,

then:

$$\frac{3.3V - 3.25V}{3.25V} \times 100 = 1.5\%$$

Line Regulation

Line regulation, like load regulation, is also expressed as a percentage of the output voltage. Line regulation, is the change in output voltage with respect to a change in line voltage, with the output load held constant. Line regulation is an important test which tells how the output voltage will behave in your system over a predetermined input voltage range.

Use Figure 4 for the line regulation set-up.

$$\text{Line Regulation} = \frac{V_{OUT}@V_{IN(max)} - V_{OUT}@V_{IN(min)}}{V_{OUT\ (ideal)}} \times 100 \quad (3)$$

Use the formula in Equation 3 for the following practical example of an MIC4575-3.3BU with a input voltage range of 6V to 24V.

- Place the switch in the 1A load position.
- Apply power to the power supply under test and monitor the output voltage.
- Set the input voltage to 6.0V and note the output voltage, for example, 3.30V.
- Set the input voltage to 24V and note the output voltage, for example, 3.33V.

Using the measurements, line regulation is:

$$0.9\% = \frac{3.33V - 3.30V}{3.30V} \times 100$$

Efficiency

Efficiency is one of the most important criteria for determining the overall performance of a power supply. Efficiency, in this case, is a function of how effectively a power supply transfers energy from its input to its output(s).

Reading Efficiency Graphs

Using the efficiency graph for Micrel's MIC4575 buck regulator (see Figure 5a), notice how as V_{IN} goes up, the overall efficiency goes down. As a rule of thumb for buck regulator topologies, V_{IN} is inversely proportional to efficiency. The efficiency graph shows that as V_{IN} is increased, the main internal switch experiences switching losses resulting in lower efficiency.

Notice how smaller loads have less efficiency. This reduction occurs as the load current approaches the quiescent current required to run the switching regulator. This means the quiescent current becomes significant compared to actual load current. It is important to observe that the quiescent current is included in the input current and input power (see Equation 4). The opposite is true of a buck regulator efficiency as the load is increased. This explains the appearance of a typical buck regulator's efficiency graph.

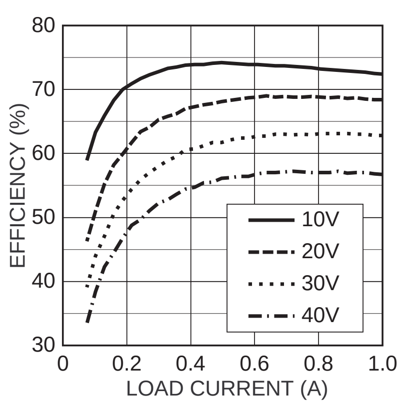


Figure 5a. MIC4575 Efficiency Graph

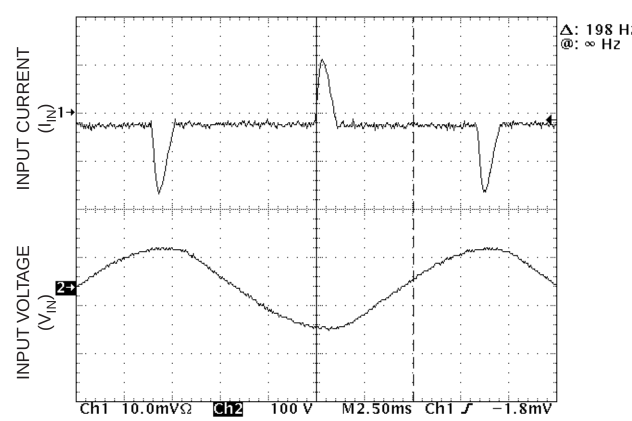
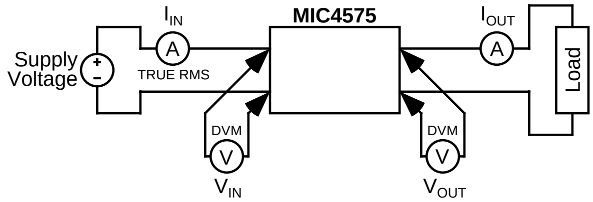


Figure 5b. Off-Line Supply Input Current and Voltage



V_{IN} and V_{OUT} must be measured right at their respective input and output pins. The input current should be measured with a true RMS meter.

Figure 6. Efficiency Test Setup Block Diagram

Input Current Measurement Accuracy

Switching power supplies have nonsinusoidal input current waveforms which can result in erroneous measurements. To avoid false readings, always use a **true RMS meter** when measuring the input current on a switching power supply.

In the case of the off-line switching power supply, the input current is always a nonsinusoidal waveform, as shown in Figure 5b, unless the supply has power factor correction. Because of this waveform, a true RMS meter—or even better, a dedicated device such as a Voltec Corp. power meter—will provide a more reliable and accurate reading for input current or power.

Determining Efficiency

Calculating efficiency requires measurement of input and output power. Efficiency is simple to calculate once you have the correct bench setup to measure input and output currents and voltages. Figure 5a provides a sanity check against your own MIC4575 readings. Use the test setup in Figure 6 for your efficiency measurements.

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100$$

Where:

η = efficiency

Then:

V_{IN} = 10.0Vdc

V_{OUT} = 3.3Vdc

I_{OUT} = 0.4A(rms)

After taking some measurements on a MIC4575:

V_{IN} = 10.0Vdc

I_{IN} = 0.165A(rms)

P_{IN} = 1.65W

V_{OUT} = 3.3Vdc

I_{OUT} = 0.4A(rms)

P_{OUT} = 1.32W

Therefore:

$$\eta = \frac{1.32W}{1.65W} \times 100 = 80\%$$

Troubleshooting and Measuring Basic Transformer Characteristics

This section discusses some of the typical measurements made on the popular flyback and forward-type transformers. The most common flyback transformer issue is incorrect polarity. See Figures 8 and 9 for a schematic diagram utilizing the two transformers types.

The polarity of a transformer means that two terminals represented by polarity dots (see Figure 8 or 9), are instantaneously in phase with respect to a common ground.

Troubleshooting Flyback Transformers

The top and bottom waveforms of Figure 7 are the voltages at test point A and B in Figure 8 respectively. These waveforms should be in phase. The polarity dot tells the winding technician that pin 1 is the start of the winding and pin 2 is the finish. If the technician winds the opposite way, the transformer is incorrect, the supply will perform poorly, and the main switch will heat and fail.

If a flyback design still performs poorly after checking the transformer polarity, measure the primary inductance. If the primary inductance is too low, the peak current on the secondary will be too high (in a step-down transformer) and may destroy the output diode. If the inductance is too high, the supply (of a discontinuous flyback) will not operate at $V_{IN(min)}$ and will oscillate. The importance of having the correct inductance in a flyback transformer is critical. (*See Application Note 18*).

The forward, buck, boost, or almost any switching power supply except resonant and flyback topologies always use a

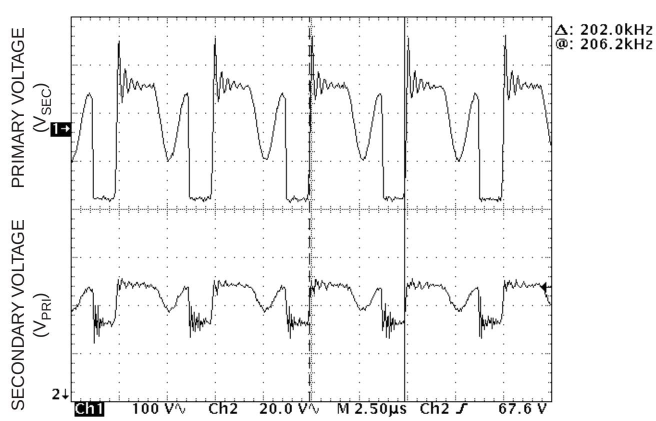


Figure 7. Off-Line Supply Switching Waveforms

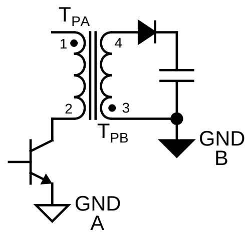


Figure 8. Flyback Topology, Partial Schematic

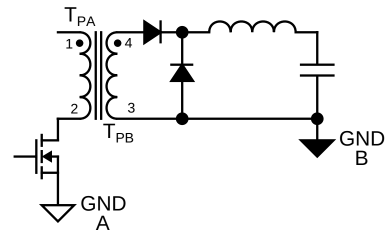


Figure 9. Forward Topology, Partial Schematic

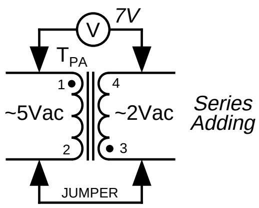


Figure 10. Flyback Transformer

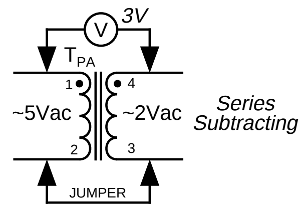


Figure 11. Forward Transformer

discrete output inductor outside the transformer. If a flyback power supply design still performs poorly, another common mistake is that the winding technician paid attention to the polarity markings, but was inconsistent when winding the secondary. This means the primary was wound clockwise and the secondary was wound counterclockwise, defeating the purpose of the polarity dots. This will appear on an oscilloscope as out-of-phase waveforms with respect to the polarity dots.

Identifying and Testing Phasing on Flyback- and Forward-Type Transformers

For flyback- and forward type-transformers, the relationship of phasing from primary to secondary can be found by using Figure 8. The rule of thumb for identifying the two is:

- Flyback transformers always have polarity dots at opposing terminals. See Figure 8.
- Forward transformers always have polarity dots at the same terminal ends and an output *power* inductor. See Figure 9.

Checking the Flyback transformer

1. Check the voltage at the flyback transformer across pins 1 and 2 and pins 3 and 4. See Figure 10.
2. The voltage is 5Vac across pins 1 and 2 and 2Vac across pins 3 and 4.

If the flyback transformer was wound correctly, the voltages should add.

Checking the Forward Transformer

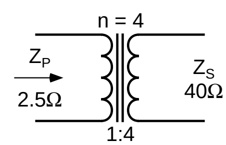
1. Check the voltage at the forward transformer across pins 1 and 2 and again across 3 and 4. See Figure 11.
2. The voltage is 5Vac across pins 1 and 2 and 2Vac across pins 3 and 4.

If the forward transformer was wound correctly, the voltages should subtract.

Testing Transformers Turns Ratio

Impedance Ratio Method

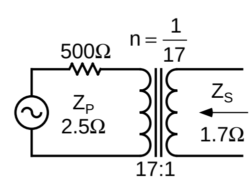
A transformer is used to step up or step down a given voltage; however, there is also a relationship between a transformers turns ratio and its impedance ratio. This relationship can be used to test a transformer for the proper turns ratio or match different impedances in a RF network. The impedance ratio of a transformer goes up by the square of the turns ratio. For example, if the transformer has a 17:1 turns ratio, then the impedance ratio is 17^2 = 289:1 impedance ratio. (Refer to



A step-up transformer has a lower Z_{IN}.

$$Z_P = \frac{Z_S}{n^2} = \frac{40}{4^2} = 2.5$$

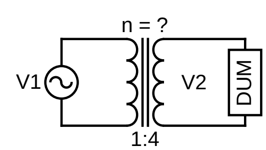
Figure 12. Step-Up Transformer



A step-down transformer makes the Z_{SOURCE} appear lower.

$$Z_S = n^2 Z_P = \left(\frac{1}{17}\right)^2 \times 500 = 1.73\Omega$$

Figure 13a. Step-Down Transformer



$$\text{turns ratio} = \frac{V1}{V2} \text{ or } \frac{V2}{V1}$$

$$\text{impedance ratio} = \left(\frac{V1}{V2}\right)^2 \text{ or } \left(\frac{V2}{V1}\right)^2$$

Figure 13b. Determining Turns Ratio

Figures 12 and 13.) Any resistive or reactive impedance placed on the primary or the secondary is transformed to the opposite side by the impedance ratio of the transformer. In Figure 12 a step-up transformer has a 40Ω resistor across the secondary. The resistance across the primary should be about 2.5Ω if the transformer has the correct number of turns. The coupling factor in transformers prevents an exact readings. In Figure 13a, a step-down transformer has a 500Ω primary impedance. Its secondary measurment should be approximately 1.7Ω.

Since the transformer turns ratio is not always known, another method is to place an ac source across the transformer. (See Figure 13b.) By placing a convenient voltage across one side of the transformer and measuring the other side, the turns ratio can be calculated by dividing the larger of the two numbers. See Figure 13b.

Troubleshooting Switching Power Supplies

The following sections are devoted to some of the common mistakes and problems with prototype switching power supplies. The most prevalent problems associated with a switcher are miswired circuits, a wrong component value, or an incorrect bench setup. When the obvious errors have been eliminated, but problems persist, the next section may help to address the more difficult problems and idiosyncrasies known to plague switchers.

Troubleshooting an Off-Line Power Supply

When troubleshooting a power supply, it is important to recognize that the supply can be divided into subsections. The best way to troubleshoot a power supply is to isolate the problem down to one section at a time. This method can be called deductive isolating. Use the schematic shown in Figure 14 for this example, which uses an MIC38C43.

Problem: Supply draws excessive startup current.

1. Look for obvious shorts or miswiring on the supply.
2. If problem persists, disconnect the output diode (D4).

If the input current is back to normal, the problem is a short on the secondary side of the power supply. If the problem persists, it is a shorted or reversed component on the primary side of the supply. By using this method, you have already eliminated half the components.

Problem: Supply tries to start but does not stay on (hiccup mode). Hiccup-mode refers to a power supply that cycles on and off.

1. Check the start-up resistors R2 and R3 to make sure they are the correct values.
2. The input voltage could be too low. Try increasing the input voltage.
3. If the problem persists, disconnect the auxiliary winding and replace it with a bench-top supply. With the bench-top supply providing 10Vdc to the V_{CC} pin of the MIC38C43, bring the ac source up to about 25Vac. If it now operates, the problem is a missing turn, open circuit in the auxiliary winding, or a wrong value for C8, R2, or R3.

Problem: Off-line supply makes an audible noise when operating.

- C13, C14, or R15 are wrong value, open, or shorted.

Problem: The supply has a high current limit.

- The current limit resistor, R9, is shorted, or its value is too low.

Problem: The output voltage is unregulated.

1. Check for 2.5V at the TL431 reference pin.
2. Check for continuity between U2b's anode and the output of the supply.
3. Check U2a's collector for 5V from the MIC38C43 5V reference output.

Oscilloscope Probe Compensation

Oscilloscope probe compensation should always be checked before taking switching power supply measurements.

For example, an output noise measurement on a 200kHz buck regulator (MIC4575) has an expected ac-coupled reading of about 20mV peak-to-peak. A combination of a 10× probe and fast rise and fall times in this application can cause false readings. Similar measurements on a low frequency switcher, such as the 52kHz LM2575 may result in distorted output noise measurements.

Low-frequency measurements made with an uncompensated scope probe will show on your oscilloscope as a distorted waveform, and in high-frequency applications the amplitude of the waveform will be incorrect. See Figures 15 through 18 for examples of uncompensated versus compensated waveforms in high- (MIC4575, 200kHz) and low-frequency (LM2575, 52kHz) applications.

Measuring Transient Load Response

By definition, transient response is the response of a system's output as a function of time to a change at its input. Transient response can be divided into three subtopics: overshoot, undershoot, and settling time.

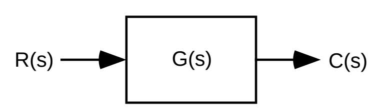


Figure 19. Open-Loop System Model

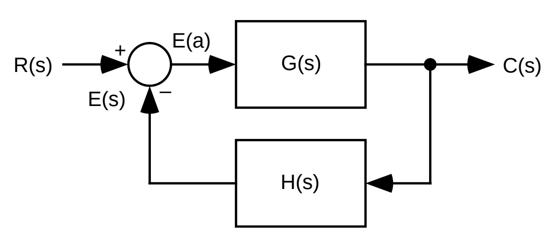


Figure 20. Closed-Loop System Model

When discussing transient response it's almost impossible not to include closed-loop feedback control systems. Simply put, this system compares the actual output with the desired output. Figures 19 and 20 are models of open- and closed-loop systems. In the mathematical model of a closed-loop system (Figure 20), R(s) is the reference output, E(s) is the error signal, and E(a) is the difference between R(s) and E(s).

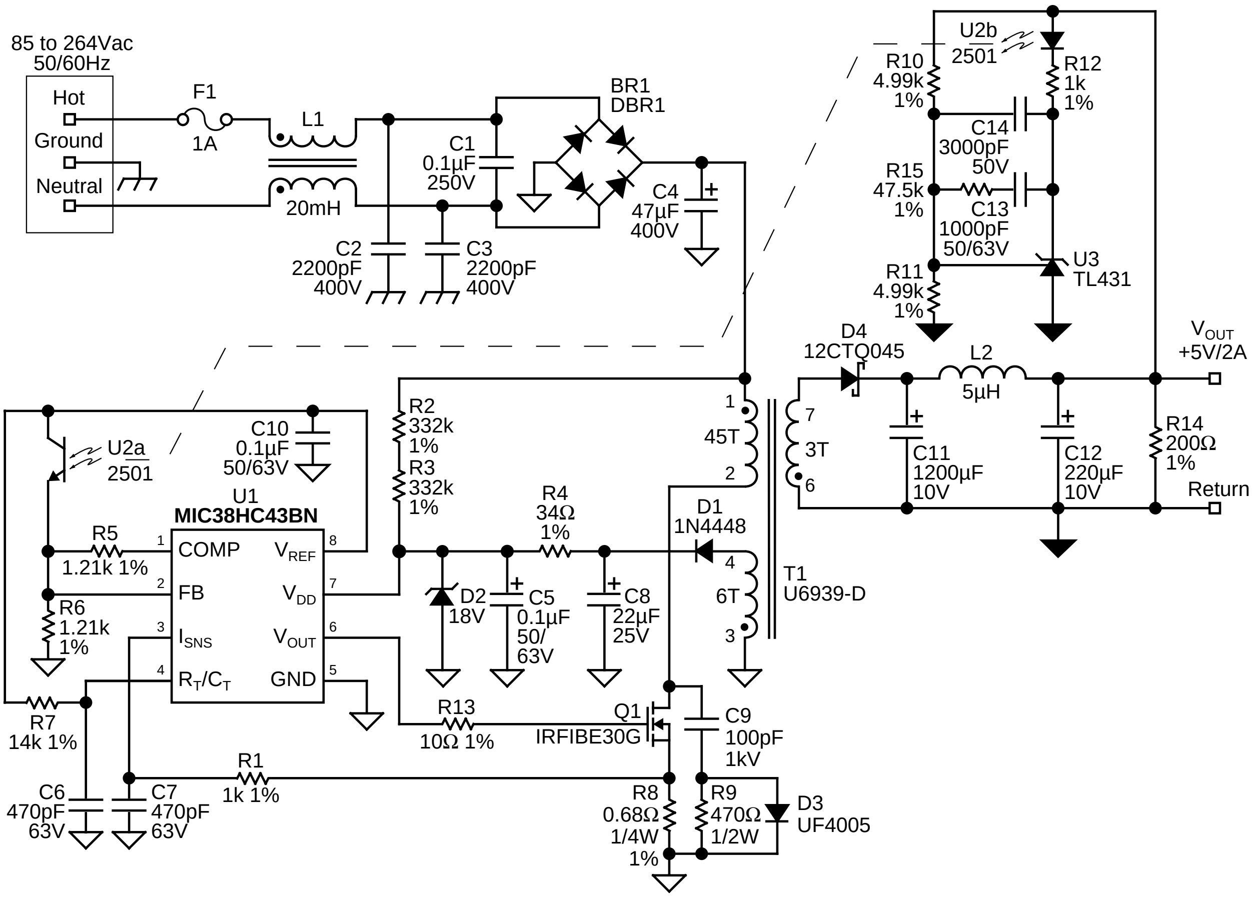


Figure 14. Off-Line Power Supply

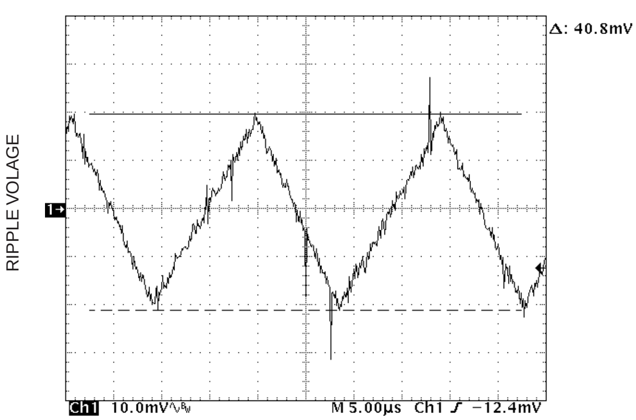


Figure 15. 52kHz Ripple, Uncompensated Probe

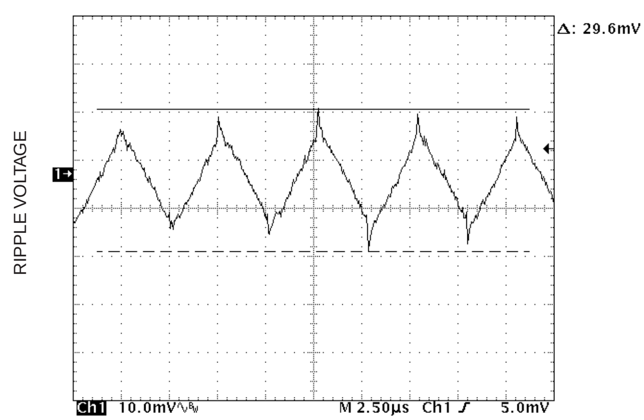


Figure 17. 200kHz Ripple, Uncompensated Probe

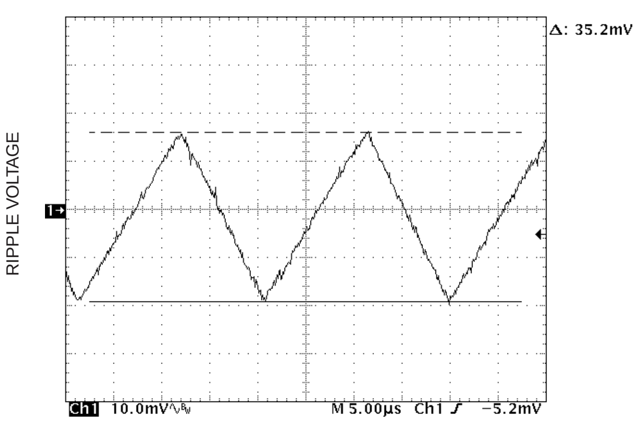


Figure 16. 52kHz Ripple, Compensated Probe

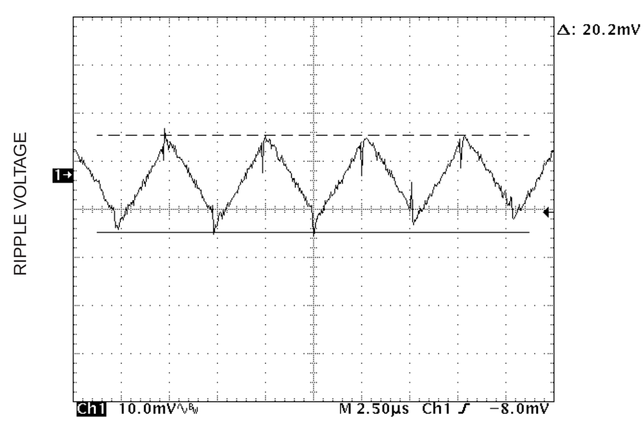


Figure 18. 200kHz Ripple, Compensated Probe

The controller G(s) adjusts its output based on E(a) the error actuating signal; until C(s), the output, attains the desired level. H(s) is the measurement block that represents a constant in most cases.

Transient load response is important because, for example, if the 5V supply in a microprocessor-based system suddenly demands more current, and the 5V output suddenly drops to 2V, the system will crash. Transient load response is improved in one of two ways: improve the feedback loop speed, or increase the output capacitor value (also called a hold-up capacitor). Using the optimum combination is the preferred method.

Overshoot (Using an MIC4575 Evaluation Board)

In a closed-loop system, specifically a power supply application, overshoot is the amount the output response exceeds the nominal output voltage. See Figure 20.

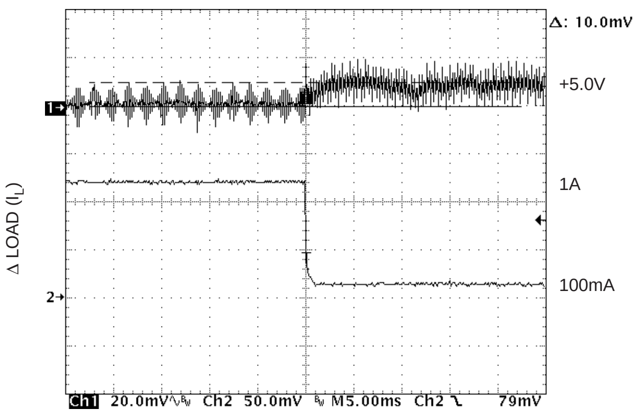


Figure 20. 1A to 100mA Load Change

Undershoot (Using an MIC4575 Evaluation Board)

In a closed-loop system, specifically a power supply application, undershoot is the amount the output response is below the nominal output voltage. See Figure 21.

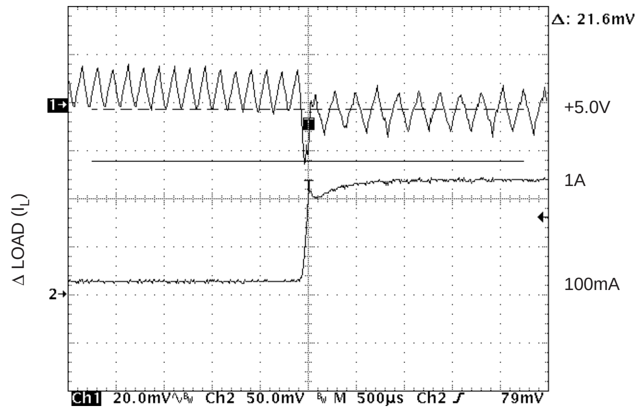


Figure 21. 100mA to 1A Load Change

Settling Time (Using an MIC4575 Evaluation Board)

In the case of a power supply application, settling time can be defined as the time required for the output to settle within the load's specified percentage limits. See Figure 22.

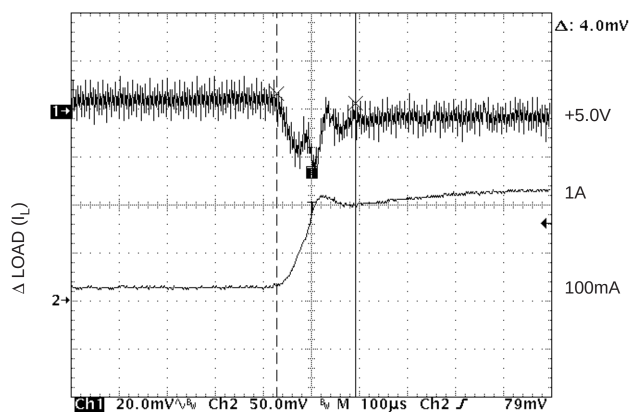


Figure 22. 100mA to 1 A Load Change

Symptom	**Likely Problem**
Excessive start-up current	Shorted input or output. Wrong inductor value. Frequency too low.
Unregulated output voltage	Check the feedback loop from output to the feedback pin on the IC for open, shorted, or wrong value components.
Excessive output voltage ripple	Wrong output filter capacitor value. Output inductor value is too low for the ESR of the output capacitor.
Audible noise	Loop stability incorrect. Check the feedback compensation components.
High current limit	Current limit set too low. Check current limit resistor.
Poor efficiency	Operating frequency too high causing excessive losses in the main FET or output diode. Wrong transformer core material.
Transformer primary inductor saturation	Primary turns missing or cracked core.

Troubleshooting Switching Power Supplies

References

Brown, Marty, *Power Supply Cookbook*, Butterworth-Heinemann, Boston, 1994

Dixon, Jeff, *Application Note 18: Off-Line Reference Design*, Micrel, Inc., 1998

Pressman, Abraham I., *Switching Power Supply Design*, 2d ed., McGraw-Hill, New York, 1998

MICREL INC. 1849 FORTUNE DRIVE SAN JOSE, CA 95131 USA
TEL + 1 (408) 944-0800 FAX + 1 (408) 944-0970 WEB http://www.micrel.com

This information is believed to be accurate and reliable, however no responsibility is assumed by Micrel for its use nor for any infringement of patents or other rights of third parties resulting from its use. No license is granted by implication or otherwise under any patent or patent right of Micrel Inc.

© 1998 Micrel Incorporated