

Off-Line SMPS Failure Modes PWM Switchers and DC-DC Converters

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ABSTRACT

Today's voltage regulator modules (VRMs) employ off-line SMPS techniques. Traditionally, they are usually discarded when they fail because they are so challenging to debug and so inexpensive to replace. Investigation of these failed modules reveals some common failure modes. Some failures are caused by other systems' passive components that fail after repeated electrical stress. Recognizing these common failure modes brings new life to a switch-mode power supply.

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Off-Line SMPS Operation

PC power blocks and other dedicated power supplies are known as *switch-mode power supplies*, or SMPS. They convert the line ac voltage to low-voltage high-current dc. A typical SMPS can be simplified as shown in the block diagram of Figure 1. Figure 2 illustrates a typical push-pull switcher circuit.

In most switching supplies, the 120-Vac or 240-Vac input first passes through a fuse and a line filter. The ac input is then rectified by a full-wave bridge rectifier and filtered by a pair of high-voltage capacitors. This creates two high-voltage sources from either side of the full-wave bridge, one positive and the other negative. For 120 Vac at 60 Hz the dc voltage is $V_{rms} \times 1.414 \times 2 = 338 \text{ V}$ ($\pm 169 \text{ V}$). The ripple is now 120 Hz, which is easily filtered by the high-frequency dc-to-dc power stage.

A pair of transistors is then used to switch these high voltage supplies across the primary winding of a transformer. This switching action is very fast and typically switches at speeds around 50–300 kHz. An integrated circuit such as the TL5001 or TL494 is commonly used to control the transistors at this switching rate. This IC not only controls the switching speed of the transistors, but also controls the conduction time of each transistor. This *pulse-width modulation* (PWM) sets the *on* and *off* duty cycle of the devices. The output voltage of the power supply is determined by this timing.

Other features designed into the PWM controller help regulate, stabilize, and provide the requirements for higher load current and instantaneous current. These power transistors charge and discharge the transformer primary and thus induce power to the secondary winding. Isolation between the line and the dc supply voltage is implemented using this transformer mutual coupling.

The output of the transformer (which is now a pulse-width-modulated voltage at the switching frequency) is then rectified by special high-speed diodes to change it back to dc. For the 5-Vdc output, there are usually two diodes housed in a single package. This package is usually a TO-220 or TO-218 three-leaded package. The 12-Vdc and –5-Vdc outputs each have their own pair of output diodes. These outputs are not pure dc, and require extensive filtering to remove the high-frequency component generated by the switching action of the transistors. Filtering is accomplished using a combination of inductors and capacitors in a low-pass configuration.

The output voltage of the power supply is regulated by feeding some of the output back to the integrated circuit that controls the switching transistors (see Figure 2).

Failure of the control IC can induce various power supply failure modes, from a reduction in regulation and/or response, to complete output failure. Protection within the IC invokes shutdown of all control signals, turning the module off.

Figure 1 shows a simple diagram of a typical line switch-mode power converter. This particular one accepts 240 Vac, and incorporates line isolation using a transformer's primary and secondary windings, and an optoisolator to decouple the feedback line from the dc regulated output. This block diagram symbolizes both single and synchronous transistor switch elements and the associated control IC typically used.

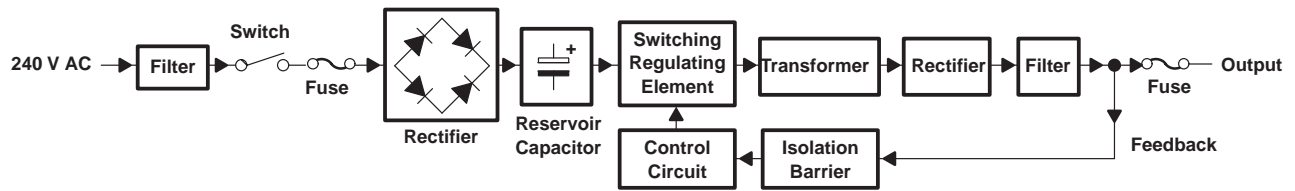


Figure 1. Typical Line Switch-Mode Power Converter

Figure 2 shows the ac and dc power paths with synchronous transistor switching elements. T1 typifies the line isolation and the output buck elements of D2, D3, L1, and C3.

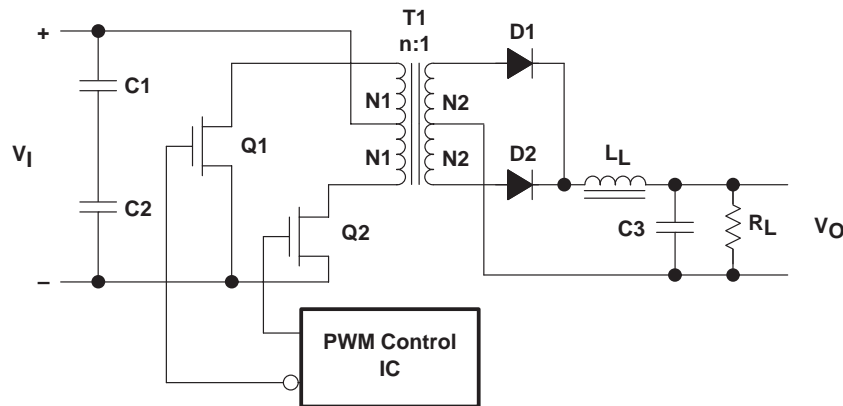


Figure 2. The Push-Pull Circuit

The more common failure modes result from the power switching devices and from passive components associated with the power supplies. Typically, failure modes do not reside in these small control signals—they are low voltage devices. These switching signals should still be checked to assure proper operation. A check of the PWM control signal at the base of the power transistor using a scope probe is a good way to verify the operation of the PWM controller.

WARNING:

Care should be taken when probing the primary-side components in an off-line power supply, since lethal voltages are present at these nodes. Isolation of ac-powered test equipment should also be required.

Care should also be taken not to load these nodes during test: using a low-capacitance scope probe is best. Even low capacitance probes can affect the waveform. Figure 3 displays the typical waveform at the input and output of these driver transistors in continuous mode. Figure 4 displays the discontinuous-mode waveform, and describes the contributions due to various components.

In Figure 3, channel 2 is the switching voltage at the collector of one of the power devices driving current into the transformer. The lower waveform of channel 1 is the actual gate signal applied by the control IC. In this case, the dc offset of this signal is -146 V .

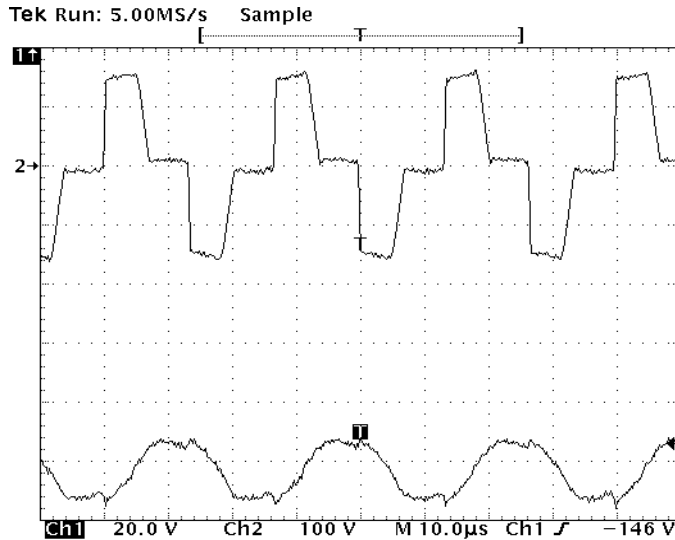


Figure 3. Typical Waveform at the Input and Output of the Driver Transistors in Continuous Mode

In Figure 4, the drain-to-source voltage drops to V_{sat} when FET is on and the inductor current increases. When the FET is turned off, the inductor current must continue to flow somewhere; as a result, the drain-to-source voltage rises to forward bias the output diode ($V_o + V_{diode}$) as the inductor current discharges to zero. When the inductor is fully discharged, the drain node is *floating* and the voltage rings due to parasitic currents, eventually returning to the input voltage.

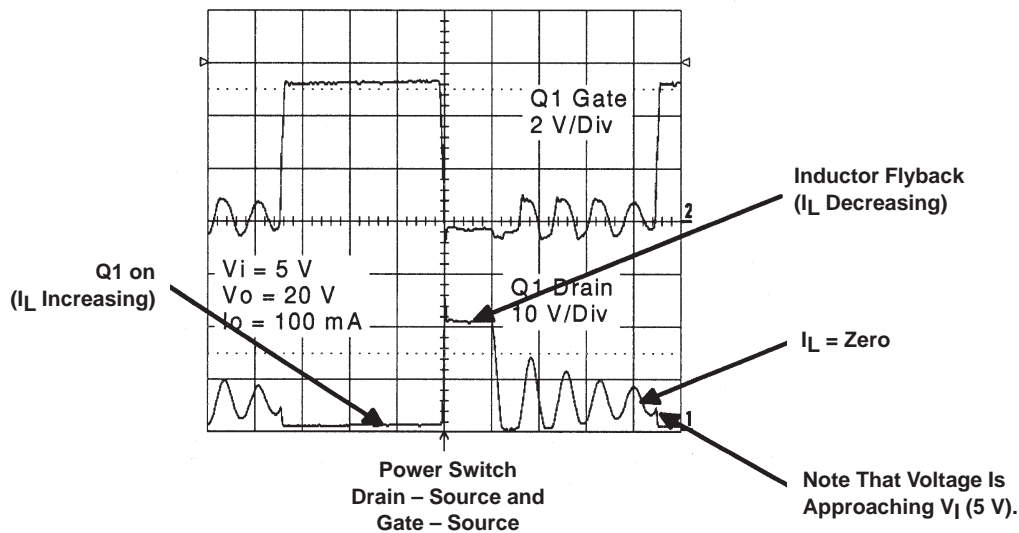


Figure 4. Discontinuous-Mode Waveform

Solution—Common Power Supply Failures

Typically, only a small number of components fail in switching-regulator power supplies. The most common failure is the switching transistors themselves. The transistors short-circuit, causing massive amounts of current to be drawn across the transformer, blowing the input line fuse.

This is the common failure mode for a bipolar transistor P-N junction during a short-load event. The high current seen at the device junction displays a typical failure mechanism. During this overcurrent, the junction depletion regions grow so large that the majority carriers occupy both doped regions, creating a very low resistive region. The heat generated can cause a thermal runaway condition. This first failure *state* is thus the short circuit of the P-N, base-collector junction.

This transistor failure is often caused by bad capacitors. It is extremely common to find output filter capacitors that are swollen or leaking electrolytic material. Any capacitor that is swollen or leaking should be replaced. The output filter capacitors are part of the stabilization network for the power supply and should be replaced only with equivalent components to insure reliable operation.

Diode failure is another common problem. There are several diodes in a switching supply, and failure of any one of them can cause the supply to blow the fuse or to shut down. The most common diode failures are shorted 12-V or -5 -V output rectifiers. Failure of these diodes will not blow the fuse. The supply simply detects the short and shuts itself down.

Testing and Repair

All testing is done with the power off. Start by testing the pair of switching transistors. These transistors are typically mounted on a heat sink that helps them run cooler. Test them by using an ohmmeter or a digital multimeter set to the diode test range. Check each transistor for shorts between emitter and collector. Replace any bad transistors found. Although some technicians suggest replacing both of them even if only one is bad, experience shows this to be unnecessary. By the way, these transistors should always appear shorted between base and emitter when tested in circuit.

It is not necessary to test the base-emitter junction of the transistors. When the switching transistors fail, they always short between emitter and collector. If you are in doubt, pull the transistors out of the circuit to test them. If the transistors are shorted, the fuse should have blown. Be sure to test the high-voltage diodes as well. The high-voltage diodes are usually part of a bridge rectifier, although they may be individual diodes.

Next, test the output rectifiers. There are three pairs of diodes to test. One pair is for the -5 -V output. These are fairly small, approximately the same size as the ubiquitous 1N4004 with which we are all familiar. The 12-V diodes are usually somewhat larger. The two 5-V output diodes are housed together in a *dual-diode* package that looks very much like a transistor. Like the switching transistors, this diode package is mounted on a heat sink. It usually has the diode schematic symbols printed on it. This diode does not usually test properly in-circuit. Testing can be simplified by unsoldering it with a *solder sucker* instead of removing it completely from the printed-circuit board. Failures of the ± 5 -V output diodes are rarely seen. All diodes must be replaced with high-speed diodes—otherwise the power supply generates excessive noise.

Follow these tests by replacing any defective output capacitors, and fire up the power supply. The supply should be tested under load. Use a 5- Ω , 25-W resistor or equivalent as a *dummy load*, connected between the 5-V output and ground (DC COM). This should draw 1 A from the supply, which is adequate for test purposes. If the supply is still inoperative, the integrated circuit may be bad. Test the IC by removing it from the printed-circuit board and installing it in a power supply that is known to be good. I have a spare power supply with a socket in it that I use exclusively to test integrated circuits. Just about all the supplies use the same IC, a type 494. Equivalent integrated circuits are: TL494CN, μ A494, and μ PC494C.

Negative Voltage Output Too High

Most switching-regulator power supplies have three dc outputs. One is the main 5-Vdc output that powers the computer system. The others are the 12-V and -5-V outputs. These dc outputs are often used to power the sound generating system and the audio amplifier itself. When testing a power supply, it is important to check all three outputs.

When a switching-regulator power supply fails, all three outputs usually drop to zero volts. Sometimes, however, the output voltage may rise. If you find that the 5-Vdc and 12-Vdc outputs are normal, but the -5-Vdc output is too high (more than -6 Vdc), try replacing the -5-V output filter choke. It's easy to locate the -5-V filter choke, even without a schematic diagram. Just follow the trace on the printed-circuit board back from the -5 Vdc output of the power supply. You will eventually come to a component that may look something like a capacitor but is clearly labeled *L* on the board and is generally accompanied by the schematic symbol for a coil as well. The coil is wound on a ferrite coil and covered with a plastic sleeve that has been heat-shrunk over it. Examine the coil; if the covering is melted or missing entirely, the coil may be bad.

Output Capacitor Replacements

When replacing the output filter capacitors, it is a good idea to change them all, unless they can be tested and are good. Testing of the suspect capacitor should be done with a capacitance meter. It is best to test the capacitance and leakage resistance at the operating voltage or maximum voltage the cap can withstand.

Output Diode Replacements

Output diodes are a common failure item in the switching-regulator power supply. Around twenty-five to thirty percent of them are found to have bad output diodes. There are three pairs of output diodes: one pair for each of the outputs: ± 5 Vdc, 12 Vdc, and -5 Vdc. These are not ordinary diodes—they are special, high-speed schottky *fast-recovery* diodes. These diodes are made to handle the very fast switching frequencies of 50 thousand cycles per second (20 μ s).

The 5-V diode assembly rarely needs to be replaced in a switching-regulator power supply. The 12-V and -5-V output diodes are the most common failures. It is normal for these diodes to test bad when doing in-circuit checks. There is usually a low-ohm resistor (normally around 100 Ω) across the output of the power supply that causes a very low reading when checking the 12-V or -5-V output diodes. Most people unsolder and remove one end of each diode to test it, but you can usually bypass this step. When these diodes fail, they generally short completely. Instead of reading around 100 ohms, you will get a reading close to zero ohms: a dead short.

Substitute Diodes

The 12-V output diodes are usually rated at 3 amps. The -5-V output diodes are often similar. Good engineering practice dictates that high speed, *fast-recovery* diodes be used in this circuit. Normal diodes have been found to fail prematurely due to their higher switching losses and subsequent thermal stress, and as such they are unacceptable as substitutions.

Conclusion

Understanding the dead SMPS and the suspect power device stages helps provide clues about the causes of failure. The process simplifies as you work on understanding these power supplies' *weak links*. This work is worth the effort when you consider that many power supply repairs are brought about by the replacement of a single diode or transistor.

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