ALL ABOUT SWITCHING POWER SUPPLIES

While more complex than their linear counterparts, where efficiency and size are concerns, switching supplies are hard to beat.

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Power supplies are used to convert an AC-line voltage into some fixed or variable value of DC voltage and current. The energy that the power supply delivers can then be used to drive an electrical load such as a radio, television, computer, or other circuit.

Most of us are quite familiar with the conventional linear-regulated (or "linear") supplies that are most often used for that task. While those are relatively simple and inexpensive, they are only up to 50% efficient, and can become quite large and run quite hot.

For some applications, there is a better alternative—switch-regulated (or "switching") power supplies. Those supplies use a clever technique to "chop" unregulated DC at a very high rate, then reconstruct the DC signal for use by the outside world. That high-frequency switching technique causes very little temperature rise in the supply so it can run much cooler. Also, smaller components can be used in building a switching supply, so the supply can be manufactured in a smaller package. However, the key advantage to those supplies is high efficiency—switching supplies can reach an efficiency of 85%.

In this article, we will examine switching power supplies in depth. We will look at some of the circuit variations and explain their theory of operation. We'll also look at some typical applications, the advantages and disadvantages of both switching and linear supplies, and even some basic repair and calibration issues.

Let's start our discussion by looking at Fig. 1. That illustration shows a block diagram for a simple switching power-supply circuit, and highlights each major segment for closer inspection. The first section we'll look at are the rectifiers.

Rectifiers. One of the key steps in converting an AC signal into DC is rectification. In rectification, a network of semiconductor diodes works to pass only one polarity of AC to the rest of the circuit. The single-polarity alternating signal is called "pulsating DC."

The first rectifier normally found in the switching supply is the input rectifier. It directly performs the initial conversion of AC line voltage into pulsating DC. A bridge rectifier, such as the one shown in Fig. 2A, is almost always used as the primary rectifier network since the design develops its own ground reference and isolates the rest of the supply from the AC line.

Use caution when working with the input rectifier circuit. The 120-volts AC at the input of the rectifier can easily develop up to 160-volts DC across the input filter. Those voltages can be dangerous and must always be treated with respect.

The second rectifier in a switching supply is the output rectifier. A variety of rectifier circuits could be used here. The simplest, but least effective rectifier is the half-wave rectifier shown in Fig. 2B. More often, the full-wave rectifier of Fig. 2C is used as the output rectifier; that's because it strikes an acceptable compromise between simplicity and effectiveness.

The chief drawback of the full-wave rectifier is that it requires a center tap in the secondary winding of the transformer to serve as the ground reference. Because of that, the bridge rectifier shown in Fig. 2D is also commonly used; a bridge rectifier requires more diodes, but eliminates the need for a secondary center tap at the transformer.

There are two important factors to keep in mind when working with rectifier diodes in a power-supply application—Peak Inverse Voltage (PIV) and Forward Current (I_F). The PIV refers to the maximum voltage that the diode can stand in the reverse-biased (or off) state. A good rule of thumb is for the PIV to be at least twice the peak voltage applied to the network, plus a 50%

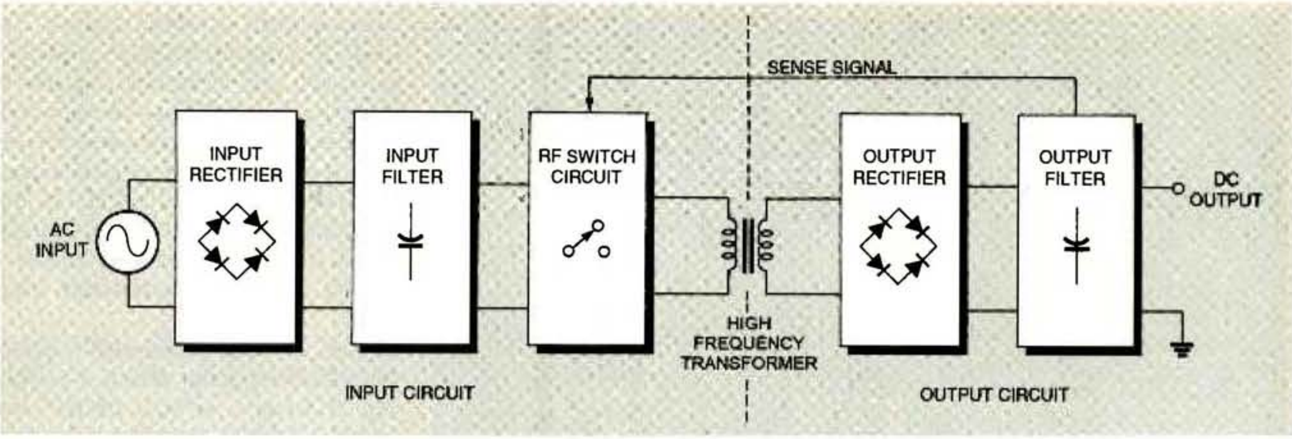


Fig. 1. This block diagram of a simple switching power supply highlights the major sections of the circuit.

safety margin. For example, if the input rectifier diode will be exposed to an AC line voltage of 115 V_{rms}, the peak voltage is $V_{rms} \times 1.414$ (115 $V_{rms} \times 1.414 = 162\ V_{PK}$). The minimum PIV for those diodes should then be (162 $V_{PK} \times 2$) + (162 $V_{PK} \times 0.5$), or 405 V_{PIV}. Higher PIV ratings are acceptable. Common rectifier diode PIVs are 50, 100, 200, 400, 600, and 1000 volts.

Forward current is the maximum amount of current that the diode can pass in the forward-biased (or on) state. It should exceed the maximum expected current by at least a 50% safety margin. As an example, if 1 amp is expected to flow in the input rectifier, the rectifier diodes should have an I_F rating of (1 amp) + (1 amp × 0.5), or 1.5 amps.

Filters. Filters are used extensively in switching power supplies to smooth out the pulsating DC from the rectifiers to form a steady DC signal. As with linear supplies, capacitors are usually used as filters in switching supplies.

Capacitors are energy-storage devices that will charge up to the peak level of pulsating DC, then discharge slightly between pulses to sustain current to the load. Figure 3 shows the effects of filtering on a pulsating-DC signal—a larger current drain will discharge filter capacitors more deeply than a small current load. That charge and discharge signal across the filter is called ripple.

Turning back to our block diagram, the input filter operates at the frequency of the line voltage (50 to 60 Hz), so a fairly large value of capacitance is usually needed—a value between 1000 and 2200 mF is typically used. Additional capacitors can be added in parallel to increase the total amount of filter capacitance and allow more energy storage. That means that there will be less discharge between pulses—therefore, ripple will be lower. Use extreme caution when dealing with values of capacitance above 5000 mF. Those can store enough energy to become a shock hazard.

Since the capacitors used in the output filter will be operating at the frequency of the RF switching circuit (20 kHz or more; more on that later), much smaller values can be used there. Effective filtering of the high-frequency AC can be accomplished using values up to 470 mF.

When selecting capacitors for use here (or in any application), the working-voltage rating (WVDC) must be considered. Here, the working voltage should be more than 50% above the peak voltage of the pulsating DC.

As an example, if the output filter is being fed by pulsating 24 VDC from the output rectifier, the peak voltage from those pulses is approximately 24 V × 1.414, or 34 V_{PK}. After adding a 50% safety margin, the working voltage would be (34 V_{PK}) + (34 $V_{PK} \times 0.5$), or 51 WVDC.

High-Frequency Transformer. A transformer is used to convert high-voltage, chopped DC into a lower voltage secondary AC signal. Figure 4 shows a generic transformer that interfaces the input and output sides of a typical switching power supply. The transformer used in the switching supply must operate at the frequency of the switching circuit (20 kHz or higher). A conventional 60-Hz power transformer will not work at high frequencies. What is needed instead is a small, light, transformer designed for optimum magnetic coupling at the switching frequency. Turns of wire wrapped around a toroidal coil are often used.

Even though the size and shape of the switching supply transformer may be different than that of 60-Hz transformers, the principle of "magnetic coupling" remains the same. That is, the high-voltage pulsing applied to the transformer's primary windings will generate a strong magnetic field that will alternate as the DC pulses on and off. The core of the transformer carries that field to the secondary windings where an alternating signal is generated. That principle is also known as "transformer coupling."

RF Regulator/Switching Network. The heart of every switching power supply is the RF regulator, also known as the switching regulator. It is that critical circuit that rapidly chops the filtered DC from the input filter at 20 kHz or higher. That circuit is also responsible for providing the regulation necessary to keep the DC output constant.

Although there are several variations of switching circuits, the Pulse-Width-Modulation (PWM) technique is by far the most popular. Figure 5 is a block diagram of a basic PWM switching circuit.

That circuit operates as a

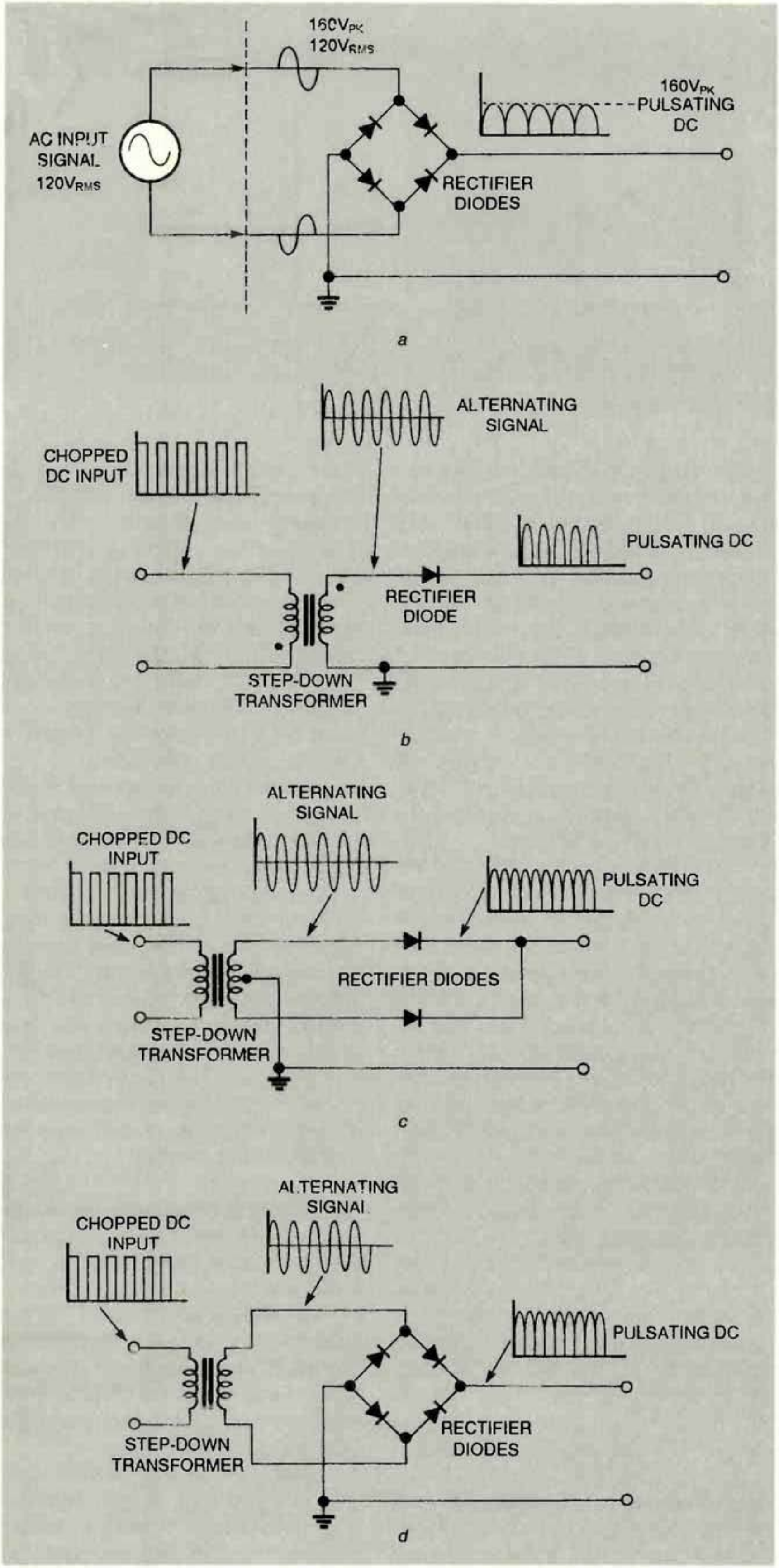


Fig. 2. A switching supply contains both an input and output rectifier. The input rectifier is usually a bridge type as shown in A. The output rectifier could be a half-wave (B), full-wave (C), or bridge (D) type.

"closed-loop" control network. The final DC output voltage is constantly sampled and checked against a factory-set reference voltage. That sample creates an error signal in an error amplifier. The error signal is used to control the pulse width of the switching signals out of the pulse-width modulating circuit, which is usually a variable pulse-width oscillator.

The varying pulse-width signal from that oscillator drives a switching transistor, which chops the unregulated DC from the input filter at a high frequency. A high-frequency step-down transformer reduces the high-voltage pulses into a low-voltage alternating signal. The "new" AC signal is then re-rectified and re-filtered in the output circuits to form the final DC output voltage. The output is sampled again and used to adjust the error signal accordingly. That "closed loop" control will continue as long as the supply is turned on.

It is the constant checking and adjustment of the closed-loop system that allows the switching supply to maintain its constant output voltage. As load conditions change, the DC output voltage will tend to vary. Those variations will be sensed by the switching circuit and compensated for automatically.

Now that we've seen how a basic switching regulator works, it is time to look at some variations and applications.

The Hybrid Switching Regulator. It is not always necessary to use a high-frequency transformer in switching designs. The transformer is used only to convert high-voltage pulses to a low-voltage signal. If the unregulated DC into the switching circuit is already at a useful voltage, then transformation is unnecessary. As an alternative, a standard 60-Hz power transformer can be used to step down the AC line voltage before the input rectifier, as shown in Fig. 6. Notice the striking similarity between the input portion of Fig. 6 and a normal linear DC supply. That type of hybrid circuit combines the simplicity of linear supplies with the efficiency of switching circuits.

A working 5-volt DC, 500-mA

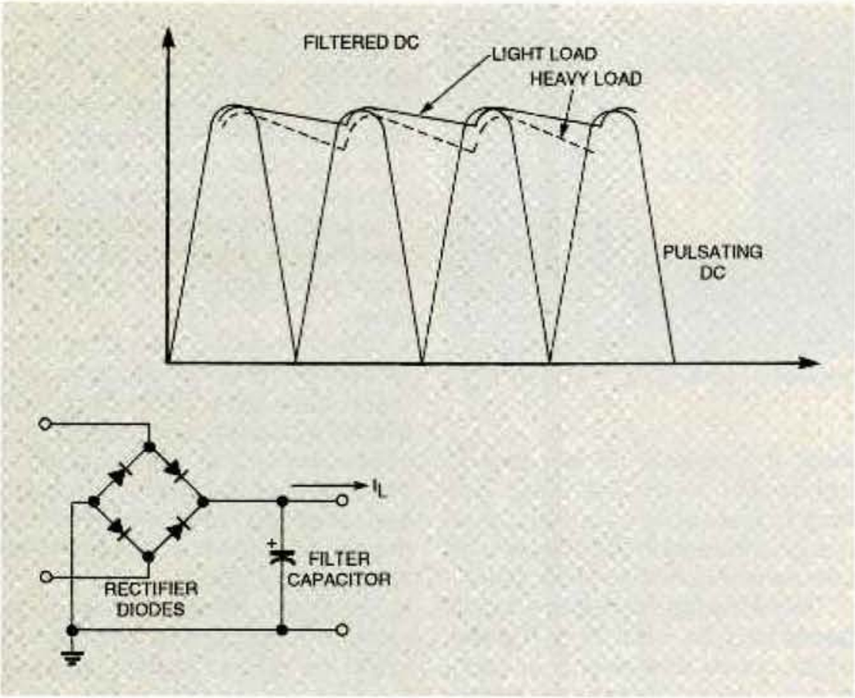


Fig. 3. The effects of filtering on a pulsating-DC signal: A larger current drain will discharge filter capacitors more deeply than a small current load, and the charge and discharge signal seen across the filter is called ripple.

power supply based on that concept is shown in Fig. 7. In it, a National Semiconductor LM341 linear voltage regulator is made to oscillate, and performs the actual conditioning of the DC output signal. Oscillation frequency in the circuit is governed by the ratio of R2 and R3, with feedback being delivered by inductor L1. The actual switching of the unregulated DC is performed by Q1.

The Flyback Switcher. The flyback switching configuration, shown in Fig. 8, is generally found in switching supplies up to about 100 watts. As can be seen in the diagram, very few components are needed to form that type of circuit, which makes it an economical arrangement for low-power supplies.

The high-frequency transformer is critical in this application, since it not only steps down voltage, but provides isolation and current limiting from the AC line. The primary and secondary windings are wound in opposing directions so that when the pulse control circuit turns on the transistor, current flows through the transformer, but the output rectifier does not conduct. When the transistor turns off, primary voltage reverses and has a "flyback" effect that allows current to flow through the output rectifier to the output filter. The pulse width controls the energy stored in the transformer—thus controlling (or regulating) the ultimate DC output voltage.

Flyback switching is limited to about 100 watts due to the current requirements of the transformer and the limitations of peak current in the switching transistor. For applications above 100 watts, the forward switching circuit, which is discussed next, is often used.

The Forward Switcher. A forward switching circuit like the one shown in Fig. 9 is most effective in 80- to 200-watt supplies. The circuit represents a serious improvement in ripple suppression as it uses a bridge rectifier, which by nature of its design, provides much less ripple than the half-wave rectifier used in the flyback switcher. To reduce ripple further, an inductor (or "choke") could be added in series with the filter capacitor. Then, when the switching transistor is on and the output rectifier is conducting, the choke will establish a potential across itself. When the switching transistor turns off and current stops in the output rectifier, the polarity of the choke's potential will reverse and provide some extra current to help sustain the load, further reducing ripple.

A slightly different pulse-control circuit is used with the forward switcher. That is necessary since the variations in the output current require changes in pulse-timing parameters to provide optimum performance. Like the flyback switcher, however, the pulse-control circuit still controls the energy delivered to the transformer, which translates into control of the DC output voltage.

Push-Pull Switcher. Above 200 watts, a more sophisticated approach is needed. A push-pull switching circuit is a high-capacity design that can be used in switching supplies up to 600 watts. In that type of switching arrangement, shown in Fig. 10, two independent pulse-width modulation circuits are used to drive each side of the switching-transistor network, which allows high currents to be developed in the supply.

Ripple in the push-pull circuit can be significantly reduced by carefully balancing the timing of each PWM circuit. Done properly, that allows the outputs of push-pull circuits to have the lowest ripple content of any switching supply.

Notice that the output rectifier and the output filter of that circuit are essentially the same as the forward switcher. Two sensing signals are taken from the DC output to serve as sample voltages in each pulse-width modulator.

Switching-Supply Disadvantages. While switching supplies offer many advantages, they are far from ideal and present many problems of their own. For example, switching power supplies are highly efficient because the high-energy, short-duration DC pulses (chopped DC) created by the high-frequency switching cause very little power dissipation—and therefore very little power wasted—in the switching transistor. That, in turn, reduces the power loss in the system. Less power dissipation also means that less

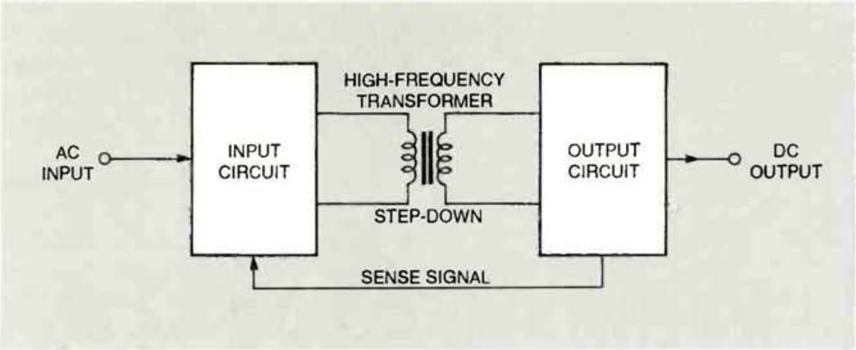


Fig. 4. As shown here, a high-frequency transformer is used to couple the switching supply's input and output circuits.

heat is generated in the power supply, which can extend the working life of the semiconductor components.

However, in order to achieve that advantage, DC is usually chopped at frequencies of 20 to 30 kHz, and switchers are currently being built to operate at up to 500 kHz; units that switch at up to 1 MHz will be available in the near future. But, each of those operating frequencies fall well within the RF (radio-frequency) spectrum. As a result, it is possible for any and all conductors in the switching portions of the supply to act as antennas and transmit those frequencies over remarkably long distances.

Under the right conditions, the RF generated by switching supplies might cause interference to other nearby pieces of electronic equipment. Even the very circuits that the supply is meant to drive might be susceptible to the disturbances that RF can cause. With that potential for noise production, it is important to know that there are several types of circuits where switching supplies probably should not be used: Extremely sensitive radio receivers and electronic instruments that must accurately measure small signals are just a few examples of that.

In spite of those difficulties, there are a variety of techniques that are used to combat the effects of noise:

- Careful shielding and grounding of the switching components and outer case can go a long way toward reducing transmitted RF.
- Interconnecting cables used in the vicinity of the supply should be well shielded, and the shielding should be common-grounded to the supply circuit.
- Electronic filtering components such as capacitors and inductors could be added to the design of the supply to suppress many of the RF emissions.
- Changing the physical orientation and position of components in the supply, as well as the location of the supply itself can alter (and

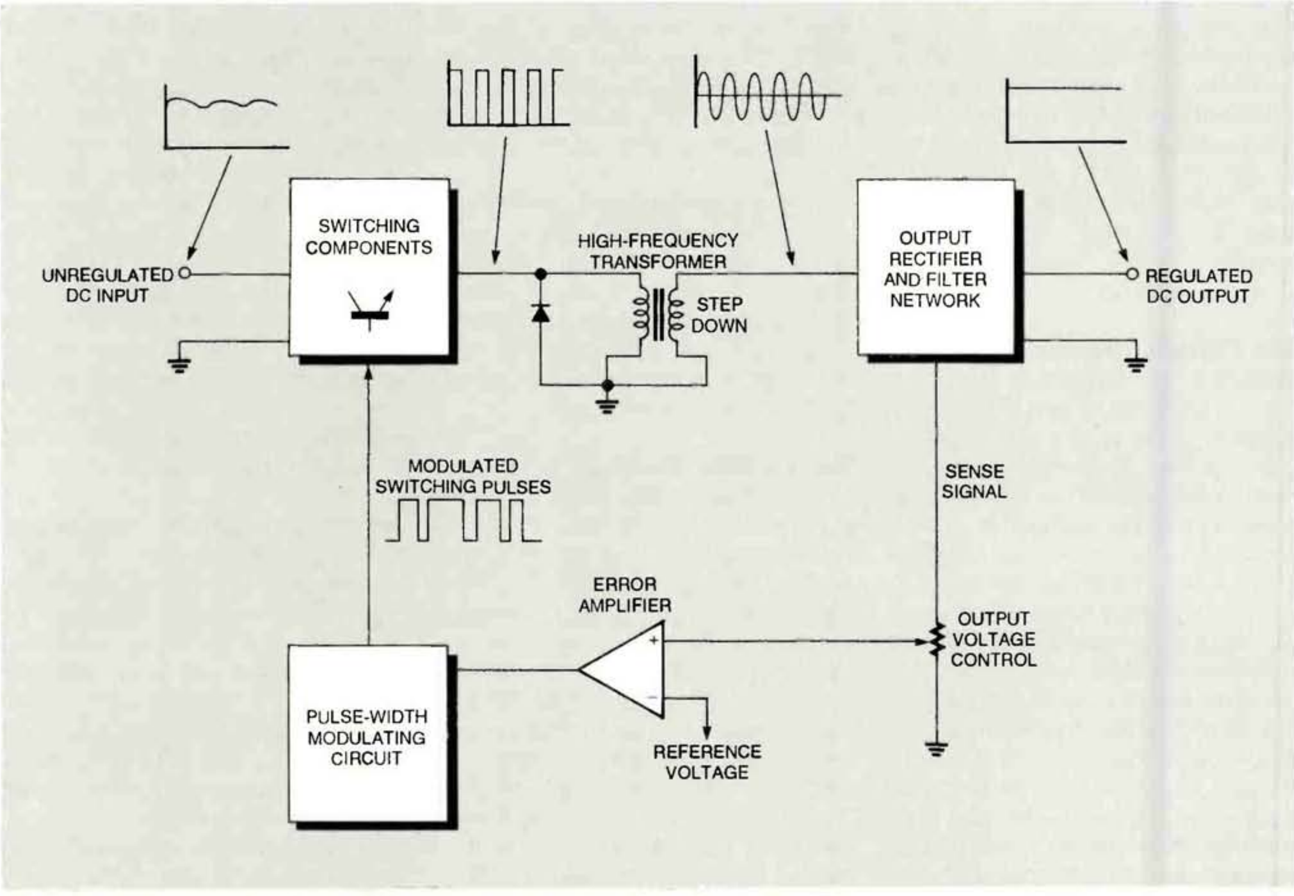


Fig. 5. The switching network used in a switching supply is shown here in block-diagram form. That circuit operates as a "closed-loop" control network.

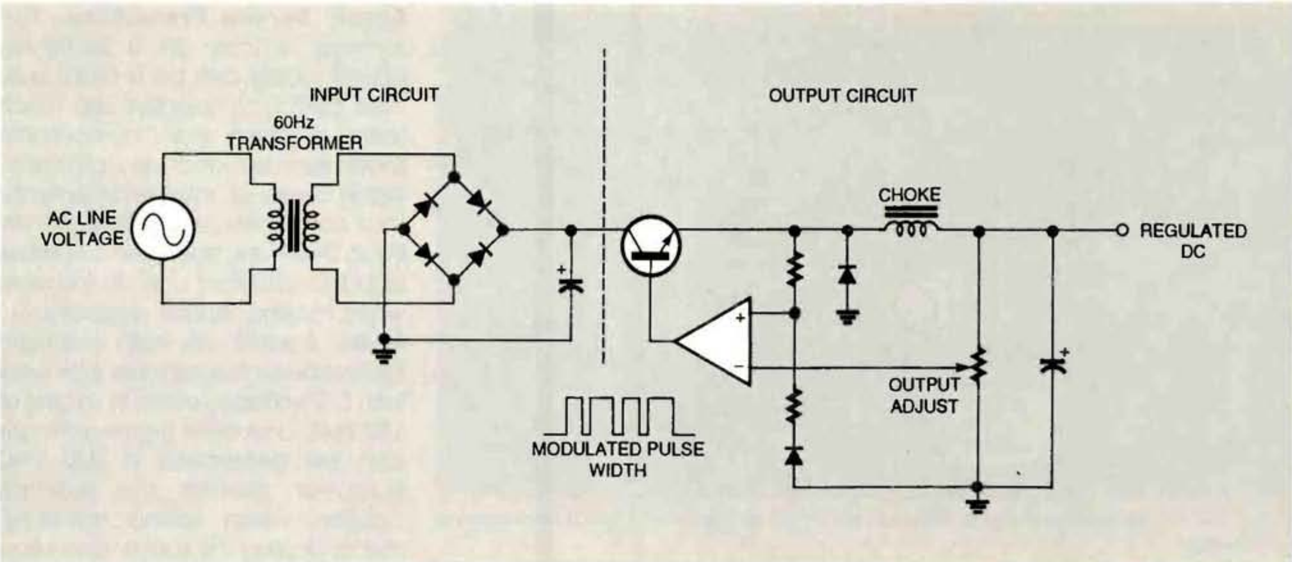


Fig. 6. In the hybrid switching supply, a standard power transformer is used to step down the AC line voltage before the input rectifier. This design combines the simplicity of a linear supply with the efficiency of a switching supply. It also eliminates the need for the high-frequency transformer.

sometimes reduce) the effects of RF outside of the supply.

When working with new switching power-supply designs, be prepared to experiment with different layouts and techniques to optimize performance. Often, noise and grounding problems may have to be solved by trial and error. Switching supplies must be designed to conform to FCC Class B requirements, as well as the European standard VDE 0871 for Class B RF products.

A switching power supply's ability to continually adjust the output voltage is not quite as good as that of its linear counterparts. That is because it takes a certain amount of time to correct the width of each pulse. If the demands of the load change, it could require several pulse cycles to fully compensate for the change. A linear regulator, on the other hand, is able to compensate for continuous load changes almost instantly.

As an example, consider a switching power supply providing an output of 5 volts at 1 amp. If the load should change suddenly and draw 2 amps, the output voltage from the supply will tend to drop. Of course, the sense signal will feedback to the PWM circuit, which will adjust the pulse width and provide additional energy to the transformer to restore the original output voltage, but it can take up to ten times longer to correct for those changes than with a linear regulator.

That phenomenon also makes it more difficult to provide the rated output voltage at full load current, so switching-supply load regulation can be as low as 1%. While that seems fairly poor, especially when you consider that a well-designed linear supply can achieve better than 0.1% load regulation, it is still fine for most applications.

Ripple voltage is an undesirable signal that rides on the DC output signal. Its magnitude is greater in the output of a switching supply than a linear supply, sometimes exceeding 10 mV peak-to-peak. A

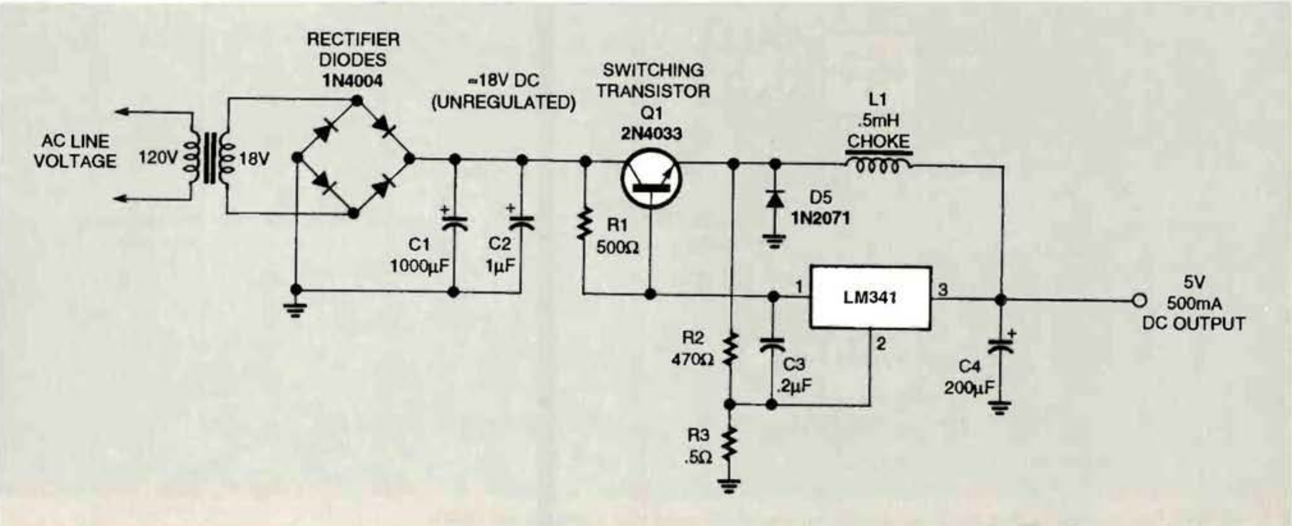


Fig. 7. The complete schematic for a practical 5 VDC, 500-mA hybrid supply is shown here.

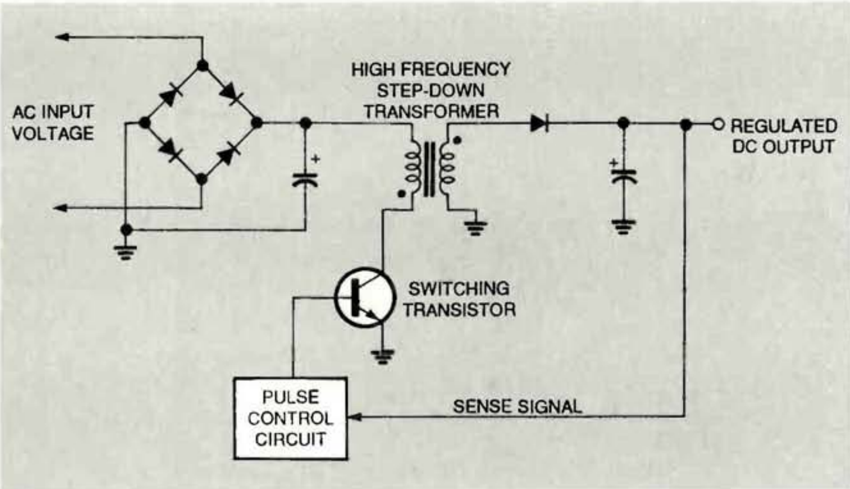


Fig. 8. For low-voltage supplies up to 100 watts, the flyback switcher shown here is an economical arrangement.

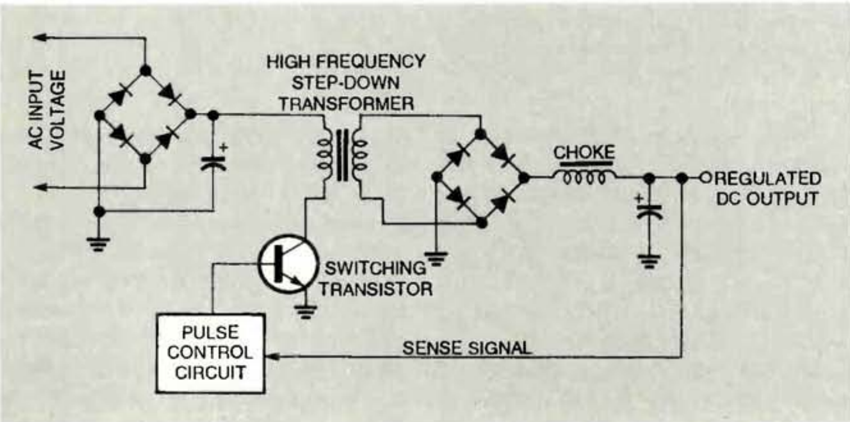


Fig. 9. The forward switcher shown here provides improved ripple suppression. It is practical for supplies delivering between 80 and 200 watts.

comparable linear supply can usually keep ripple to less than 1 mV peak-to-peak.

To make it easier to compare the advantages and disadvantages of linear and switching supplies, Table 1 compares the key parameters of each.

Supply Service Precautions. Performing service on a switching power supply can be a tricky business. Switching supplies are much more complex than comparable linear supplies, and very demanding in terms of their requirements. That can make any service job difficult. There are, however, a number of basic rules that can be followed when making service decisions.

• Be careful of high voltage! Typical switching supplies can work with DC voltages easily in excess of 150 volts, and even higher voltages can be generated in 220 VAC European models. Use extreme caution when taking measurements. Unplug the supply and allow all filter capacitors to discharge fully before doing any work on the circuit.

• Watch out for the shielding. Shielding and grounding techniques are carefully employed to suppress RF signals within the supply. Replace and re-solder any shielding, and re-secure all grounds before operating the serviced supply. Otherwise, the supply may cause unpredictable RF interference to other equipment.

• Use only exact replacement parts. A switching supply is a fairly intricate assembly of components, each chosen to provide a certain effect in the circuit. Replacing components with values other than the original value can seriously impair the supply's performance. For example, replacing a timing com-

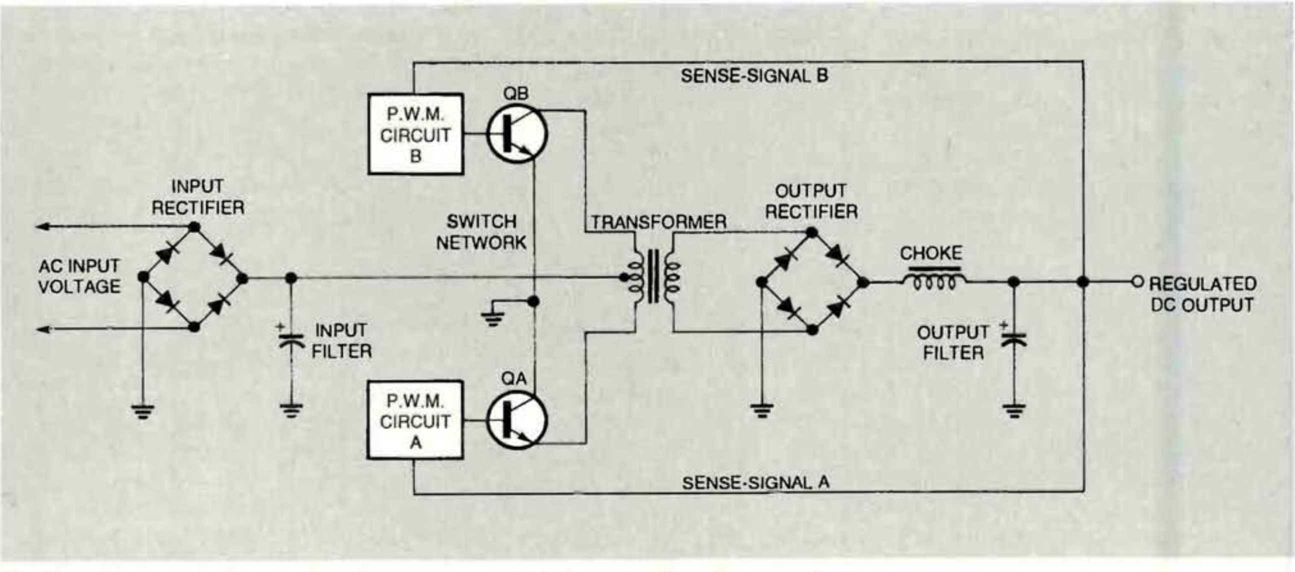


Fig. 10. While more complex than the other designs presented, the push-pull configuration shown here can be used in supplies up to 600 watts.

TABLE 1—COMPARISON OF LINEAR AND SWITCHING POWER SUPPLIES

Parameter	Switching Supply	Linear Supplty
Efficiency	60 to 80%	30 to 50%
RF Noise	Can be a problem unless shielded	Usually negligible
Transformers	Smaller, lighter, high-frequency magnetics	Requires bulky 60-Hz magnetics
Ripple	10 to 40 mV pk-pk	1 to 5 mV pk-pk
Regulation	0.3 to 1% (V_{FL})	0.05 to 0.1% (V_{FL})
Power/Weight Ratio	30 Watts/lb. (avg.)	15 Watts/lb. (avg.)
Temperature Rise	20 to 40 deg. C above ambient	50 to 100 deg. C above ambient
Reliability	Cooler operation improves the reliability	Runs much hotter and can degrade reliability

ponent in the PWM circuit with a component of a different value can effect the switching frequency, which, in turn, may render any RF suppression techniques (which have been optimized for the original frequency) ineffective. Also, use only the same type of parts. If a tantalum capacitor must be replaced, it should be replaced with a tantalum capacitor of the same value. The same is true for all other components.

• Leave calibration adjustments alone. Some versions of switching supplies may contain one or more adjustments to alter such things as current output, voltage reference, or some aspect of the switching circuit. Unless the tools and instruments are available to perform a proper service alignment, it is usually best to leave those adjustments alone. Otherwise, an improper adjustment can degrade the supply just as much as the use of an improper component.

Conclusion. The switching power supply, like all other power supplies, must convert an AC line voltage into some value of DC voltage and current that is used to power an electrical load. A switching supply accomplishes that by chopping a high-voltage, unregulated DC signal at very high frequencies (radio frequencies), transforming the chopped DC into a lower-voltage AC signal, then re-rectifying and re-filtering the AC signal into the desired DC voltage.

The primary advantage of the switching technique is efficiency. Much less power is wasted in a switching supply than in a linear supply, so more output power can usually be developed for the same amount of input power. Another advantage is compactness. Even though more components are needed to make a switching supply, they can be much smaller. That results in a smaller overall assembly.

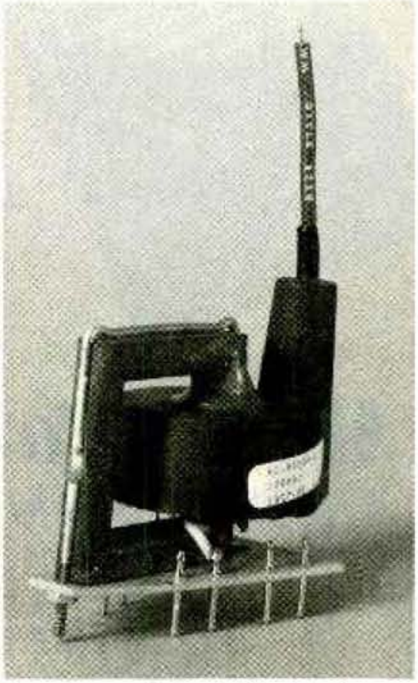
There are some disadvantages encountered in switching supplies. RF noise is the most serious of those. The high-frequency signals generated by the switching network can cause serious interference in other circuits. A variety of noise-suppression techniques are used to keep the RF under control. Regulation and ripple are not as good as in a comparable linear supply, but a switching supply will still work well in many applications.

As switching frequencies rise and RF suppression techniques become more effective, switching power supplies will become the preferred supply for high-power applications where efficiency and size are critical. Ω

PLASMA GLOBE

(Continued from page 39)

bent 90 degrees. Drill and tap a hole through the bent prong so that it can be attached to the small screw in the top cap. Whenever possible, use clear burned-out light bulbs—they work just as well as good ones.



Here is a standard television-flyback transformer. Modifying it by adding a new primary winding is the heart of the Poor Man's Plasma Globe.

Many interesting experiments can be carried out with the Poor Man's Plasma Globe. You can test different incandescent light bulbs for various effects, try lighting up fluorescent tubes, or even connect a mini-Jacob's Ladder to the output. If you try the Jacob's Ladder, don't expect much in the way of dramatics. You need a lot more than 7 amps to climb a big ladder.

The one important thing to remember with any high-voltage experiment is safety! Nikola Tesla would routinely adjust his high-voltage equipment with one hand in his pocket in order to prevent any accidental shock from zapping his heart. His death at the ripe old age of 86 is testimony to the fact that one can never be too cautious around electricity—high-voltage or otherwise. Ω