AN-556 Introduction to Power Supplies

ABSTRACT

Virtually every piece of electronic equipment, e.g., computers and their peripherals, calculators, TV and hi-fi equipment, and instruments, is powered from a DC power source, be it a battery or a DC power supply. Most of this equipment requires not only DC voltage but voltage that is also well filtered and regulated. Since power supplies are so widely used in electronic equipment, these devices now comprise a worldwide segment of the electronics market in excess of $5 billion annually.

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1   Introduction

Virtually every piece of electronic equipment, e.g., computers and their peripherals, calculators, TV and hi-fi equipment, and instruments, is powered from a DC power source, be it a battery or a DC power supply. Most of this equipment requires not only DC voltage but voltage that is also well filtered and regulated. Since power supplies are so widely used in electronic equipment, these devices now comprise a worldwide segment of the electronics market in excess of $5 billion annually.

There are three types of electronic power conversion devices in use today which are classified as follows according to their input and output voltages: 1) DC/DC converter; 2) the AC/DC power supply; 3) the DC/AC inverter. Each has its own area of use but this paper will only deal with the first two, which are the most commonly used.

A power supply converting AC line voltage to DC power must perform the following functions at high efficiency and at low cost:

1. Rectification: Convert the incoming AC line voltage to DC voltage.
2. Voltage transformation: Supply the correct DC voltage level(s).
3. Filtering: Smooth the ripple of the rectified voltage.
4. Regulation: Control the output voltage level to a constant value irrespective of line, load and temperature changes.
5. Isolation: Separate electrically the output from the input voltage source.
6. Protection: Prevent damaging voltage surges from reaching the output; provide back-up power or shut down during a brown-out.

An ideal power supply would be characterized by supplying a smooth and constant output voltage regardless of variations in the voltage, load current or ambient temperature at 100% conversion efficiency. Figure 1 compares a real power supply to this ideal one and further illustrates some power supply terms.
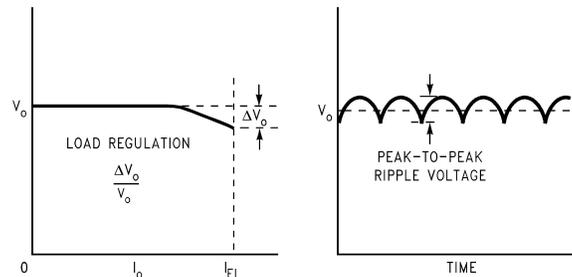
Figure 1. Real Power Supply has error compared to Ideal Power Supply

2   Linear Power Supplies

Figure 3 illustrates two common linear power supply circuits in current use. Both circuits employ full-wave rectification to reduce ripple voltage to capacitor C1. The bridge rectifier circuit has a simple transformer but current must flow through two diodes. The center-tapped configuration is preferred for low output voltages since there is just one diode voltage drop. For 5V and 12V outputs, Schottky barrier diodes are commonly used since they have lower voltage drops than equivalently rated ultra-fast types, which further increases power conversion efficiency. However, each diode must withstand twice the reverse voltage that a diode sees in a full-wave bridge for the same input voltage.

The linear voltage regulator behaves as a variable resistance between the input and the output as it provides the precise output voltage. One of the limitations to the efficiency of this circuit is due to the fact that the linear device must drop the difference in voltage between the input and output. Consequently the power dissipated by the linear device is $(V_i - V_o) \times I_o$. While these supplies have many desirable characteristics, such as simplicity, low output ripple, excellent line and load regulation, fast response time to load or line changes and low EMI, they suffer from low efficiency and occupy large volumes. Switching power supplies are becoming popular because they offer better solutions to these problems.
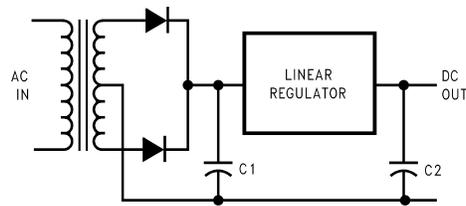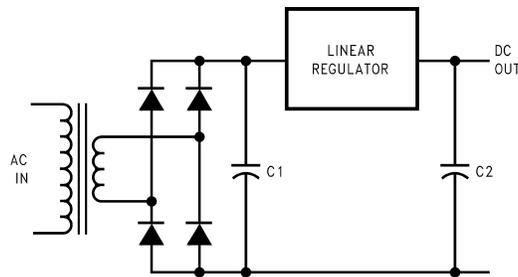
Figure 2. Center Tap Transformer Input

b. Full-Wave Bridge Input

Figure 3. Linear Voltage Regulator

3 Switching vs Linear Power Supplies

Switching power supplies are becoming popular due to high efficiency and high power density. Table 1 compares some of the salient features of both linear and switching power supplies. Line and load regulation are usually better with linear supplies, sometimes by as much as an order of magnitude, but switching power supplies frequently use linear post-regulators to improve output regulation.

4 DC-DC Converters

DC-DC converters are widely used to transform and distribute DC power in systems and instruments. DC power is usually available to a system in the form of a system power supply or battery. This power may be in the form of 5V, 28V, 48V or other DC voltages. All of the following circuits are applicable to this type of duty. Since voltages are low, isolation is not usually required.

Table 1. Linear vs Switching Power Supplies (typical)

Specification	Linear	Switcher
Line Regulation	0.02%–0.05%	0.05%–0.1%
Load Regulation	0.02%–0.1%	0.1%–1.0%
Output Ripple	0.5 mV–2 mV RMS	10 mV–100 mV$_{P-P}$
Input Voltage Range	±10%	±20%
Efficiency	40%–55%	60%–95%
Power Density	0.5 W/cu. in.	2W–10W/cu. in.
Transient Recovery	50 µs	300 µs
Hold-Up Time	2 ms	34 ms

5 Switching Power Supplies

5.1 *PULSE WIDTH MODULATION*

In the early 60's, switching regulators started to be designed for the military, who would pay a premium for light weight and efficiency. One way to control average power to a load is to control average voltage applied to it. This can be done by opening and closing a switch in rapid fashion as being done in Figure 4.

The average voltage seen by the load resistor R is equal to:

$$V_{o(avg)} = (t_{(on)}/T) \times V_i \qquad\qquad (1)$$

Reducing $t_{(on)}$ reduces $V_{o(avg)}$. This method of control is referred to as pulse width modulation (PWM).

5.2 BUCK REGULATOR

As we shall see, there are many different switching voltage regulator designs. The first one to be considered because of its simplicity is the buck regulator (Figure 5), also known as a step-down regulator since the output voltage as given by Equation 1 is less than the input voltage. A typical application is to reduce the standard military bus voltage of 28V to 5V to power TTL logic.

At time $t_{(o)}$ in Figure 5, the controller, having sensed that the output voltage V_O is too low, turns on the pass transistor to build up current in L, which also starts to recharge capacitor C. At a predetermined level of V_o, the controller switches off the pass transistor Q, which forces the current to free wheel around the path consisting of L, C, and the ultra-fast rectifier D. This effectively transfers the energy stored in the inductor L to the capacitor. Inductor and capacitor and capacitor sizes are inversely proportional to switching frequency, which accounts for the increasing power density of switching power supplies. Power MOSFETs are rapidly replacing bi-polar transistors as the pass transistor because of their high frequency capability. Since the pass transistor must not only carry load current but reverse recovery current of diode D, an ultra-fast recovery diode or Schottky diode is mandatory.
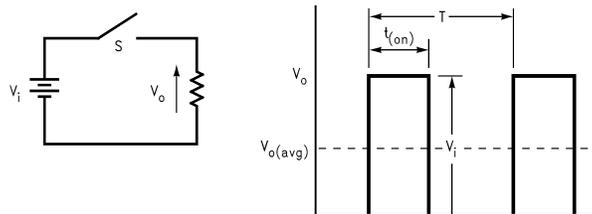

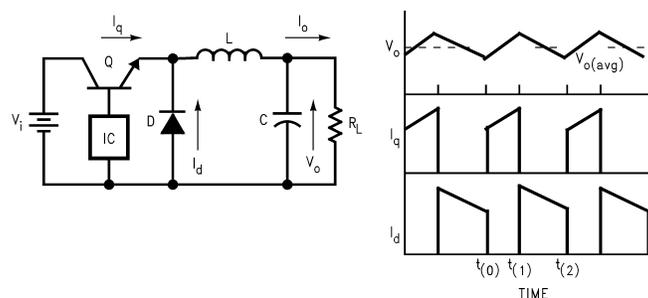**Figure 4. Example of Pulse Width Modulation**

Figure 5. Buck Regulator Circuit with Voltage and Current Waveforms

5.3 BOOST REGULATOR

A second type of regulator shown in Figure 6 is capable of boosting the input voltage. Applications for this circuit would be to increase 5V battery sources to 12V for interface circuits or even to 150V for electro-luminescent displays.

The concept of this circuit is still the same as the previous, namely to transfer the energy stored in the inductor into the capacitor. The inductor current can ramp up quickly when the transistor switch is closed at time $t_{(0)}$ since the full input voltage is applied to it. The transistor is turned off at time $_{(1)}$ which forces the inductor current to charge up the capacitor through the ultra-fast diode D. Since the energy stored in the inductor is equal to L x I x ½, the PWM IC can increase V_o by increasing its own on-time to increase the peak inductor current before switching. The transfer function is:

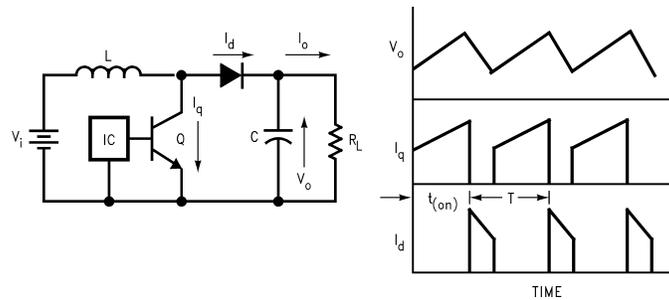$$V_o = V_{IN} (T/(T - t_{(on)})) \qquad\qquad (2)$$

Figure 6. Boost Regulator and Associated I/V Waveforms

5.4 INVERTING REGULATOR

Figure 7 shows a switching circuit which produces an output voltage with the opposite polarity of the input voltage. This circuit works in the same fashion as the boost converter but has achieved the voltage inversion by exchanging positions of the transistor and inductor. The circuit is also known as a buck-boost regulator since the absolute magnitude of the output voltage can be higher or lower than the input voltage, depending upon the ratio of on-time to off-time of the pass transistor.
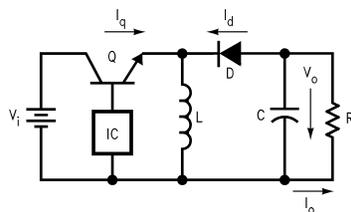

Figure 7. Inverting Regulator

5.5 FLYBACK CONVERTER

The three previous regulators are suitable for low voltage control when no electrical isolation is required. However in off-line switchers operating from 110V/220V mains, electrical isolation is an absolute must. This is achieved by using a transformer in place of the inductor. The flyback converter shown in Figure 8 is commonly used in power supplies up through 150W, which is sufficient for most personal computers, many test instruments, video terminals and the like.

Since the transformer operates at high frequency, its size is much smaller than a 50 Hz/60 Hz transformer shown in Figure 3. Within certain frequency limits, transformer size is inversely proportional to frequency.

Inspection of the switching waveforms in Figure 8 shows that the circuit behaves very similarly to the boost regulator. The transformer should be regarded as an inductor with two windings, one for storing energy in the transformer core and the other for dumping the core energy into the output capacitor. Current increases in the primary of the transformer during the on-time of the transistor ($t_{(0)} - t_{(1)}$) but note that no secondary current flows because the secondary voltage reverse biases diode D. When the transistor turns off, the transformer voltage polarities reverse because its magnetic field wants to maintain current flow. Secondary current can now flow through the diode to charge up the output capacitor. The output voltage is given by the basic PWM equation times the transformer turns ration (N2/N1):

$$V_o = V_{IN} \times (t_{(on)})/(T - t_{(on)}) \times (N2/N1) \qquad (3)$$

Voltage control is achieved by controlling the transistor on-time to control the peak primary current.
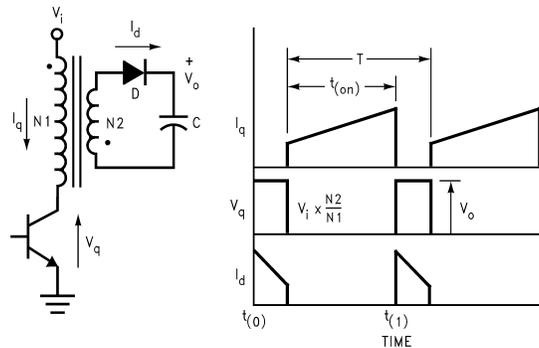
Figure 8. Flyback Converter

The flyback converter is well suited for multiple output and high voltage power supplies since the transformer inductance replaces the filter inductor(s). The major disadvantages which limit its use to lower wattage supplies are:

1. The output ripple voltage is high because of half-wave charging of the output capacitor.
2. The transistor must block $2 \times V_{IN}$ during turn-off.
3. The transformer is driven in only one direction, which necessitates a larger core, i.e., more expensive, in a flyback design than for an equivalent using a forward or push-pull design.

5.6   OFF-LINE SWITCHING SUPPLY

Based on the flyback regulator circuit, a complete off-line switching supply is shown in Figure 9. The supply is called "off-line" because the DC voltage to the switch is developed right from the AC line.

The circuit also shows the feedback loop completed from the output back to the switching transistor. This feedback loop must have isolation in order for the DC output to be isolated from the AC line. This is normally accomplished by a small transformer or opto-coupler.
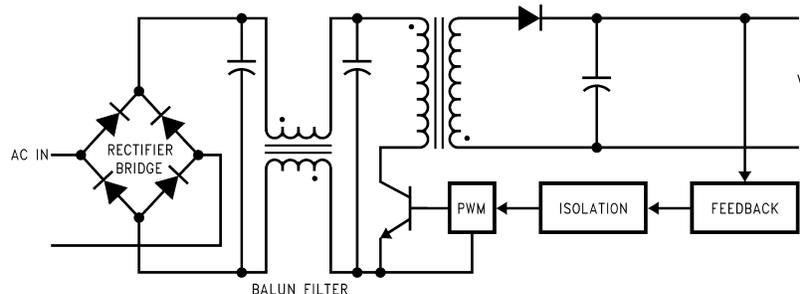

Figure 9. Complete Isolated Flyback Switching Supply

Switching power supplies designed for international usage must have selectable AC input voltage ranges of 115V and 230V. Figure 10 shows how this is accomplished for many switching power supplies.
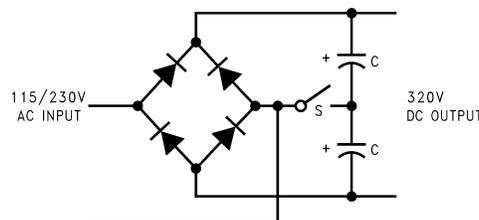

**Figure 10. Selector Switch for 115V/230V Inputs**

5.7 FORWARD CONVERTER

Although the forward converter is not as well-known as the flyback converter, it is becoming increasingly popular for power supplies in the 100W–500W range. Figure 11 shows the basic circuit of the forward converter. When the transistor is switched on, current rises linearly in the primary and secondary current also flows through diode D1 into the inductor and capacitor. When the transistor switch is opened, inductor current continues to free-wheel through the capacitor and diode D2. This converter will have less ripple since the capacitor is being continuously charged, an advantage of particular interest in high current supplies.

The relationship between input and output for this circuit configuration is:

$$V_o = V_{IN} \times (N2/N1) \times (t_{(on)}/T) \tag{4}$$

Note that the transformer shown in the above figure has been wound with a third winding and series diode D3. The purpose of this winding is to transfer the magnetizing energy in the core back to the DC supply so it does not have to be dissipated in the transistor switch or some other voltage suppressor. The turns ratio N3/N1 limits the peak voltage seen by the transistor and is normally chosen equal to 1 so that the forward converter can run at 50% duty cycle. Under this condition, the transistor must block $2 \times V_{IN}$ during turn-off.
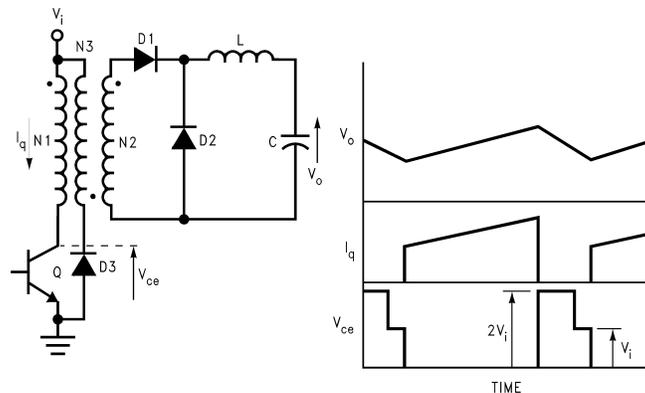
Figure 11. Forward Converter

6   Symmetrical Converters

6.1 PUSH-PULL CONVERTER

The circuit for this widely used converter is shown in Figure 12.

Transistors Q1 and Q2 are alternately switched on for time period ($t_{(on)}$. This subjects the transformer core to an alternating voltage polarity to maximize its usefulness. The transfer function still follows the basic PWM formula but there is the added factor 2 because both transistors alternately conduct for a portion of the switching cycle.

$$V_o = 2 \times V_{IN} \times (N2/N1) \times (t_{(on)}/T) \tag{5}$$

The presence of a dead time period $t_{(d)}$ is required to avoid having both transistors conduct at the same time, which would be the same as turning the transistors on into a short circuit. The output ripple frequency is twice the operating frequency which reduces the size of the LC filter components. Note the anti-parallel diodes connected across each transistor switch. They perform the same function as diode D3 in the forward converter, namely to return the magnetization energy to the input voltage whenever a transistor turns off.
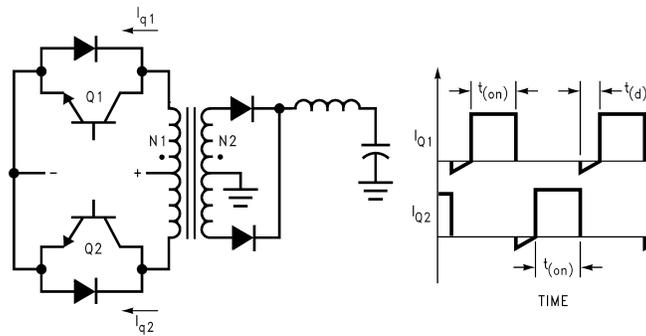
Figure 12. Push-Pull Converter

Compared to the following symmetrical converters, this circuit has the advantage that the transistor switches share a common signal return line. Its chief disadvantages are that the transformer center-tap connection complicates the transformer design and the primary windings must be tightly coupled in order to avoid voltage spikes when each transistor is turning off.

6.2 HALF-BRIDGE CONVERTER

This converter (Figure 13) operates in much the same fashion as the previous push-pull circuit.

The input capacitors C1 and C2 split the input voltage equally so that when either transistor turns on, the transformer primary sees $V_{in}/2$. Consequently note no factor of "2" in the following transfer equation:

$$V_o = V_{IN} \times (N2/N1) \times (t_{(on)}/T) \tag{6}$$

Since the two transistors are connected in series, they never see more than the input voltage V_{IN} plus the inevitable switching transient voltages. The necessity of a dead time is even more obvious here since the simultaneous conduction of both transistors results in a dead short across the input supply. Anti-parallel ultra-fast diodes return the magnetization energy as in the push-pull circuit but alternately to capacitors C1 and C2. This circuit has the slight inconvenience of requiring an isolated base drive to Q1, but since most practical base drive circuits use a transformer for isolation, this shortcoming is hardly worth noting.

6.3 FULL-BRIDGE CONVERTER

Because of its complexity and expense, the full-bridge converter circuit of Figure 14 is reserved for high power converters. Ideally, all voltages are shared equally between two transistors so that the maximum voltage rating of the device can approach V_{IN}.
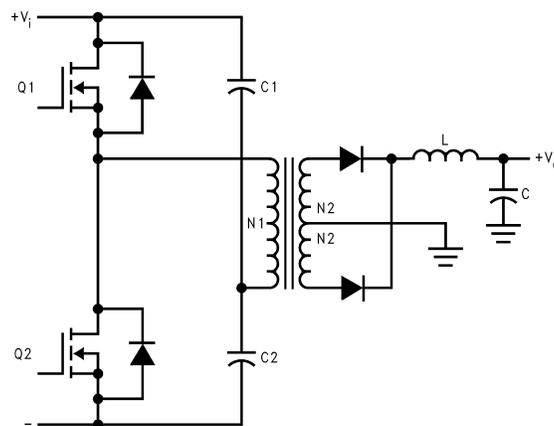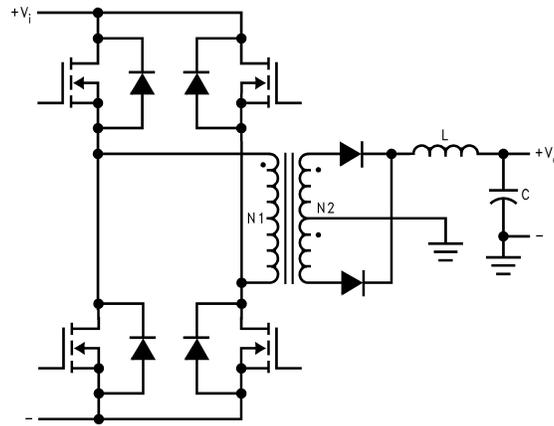

Figure 13. Half-Bridge Converter Circuit

Figure 14. Full-Bridge Converter Circuit

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