

PRACTICAL SWITCHING POWER SUPPLY DESIGN

Marty Brown

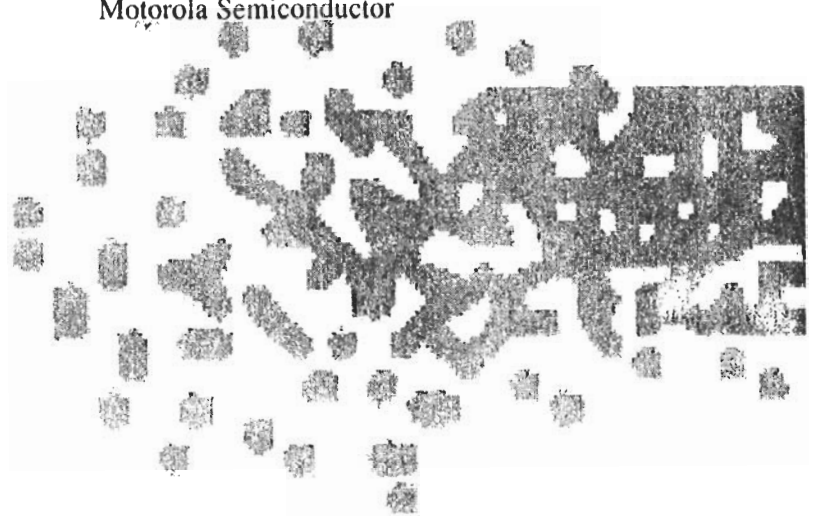


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Series in Solid State Electronics

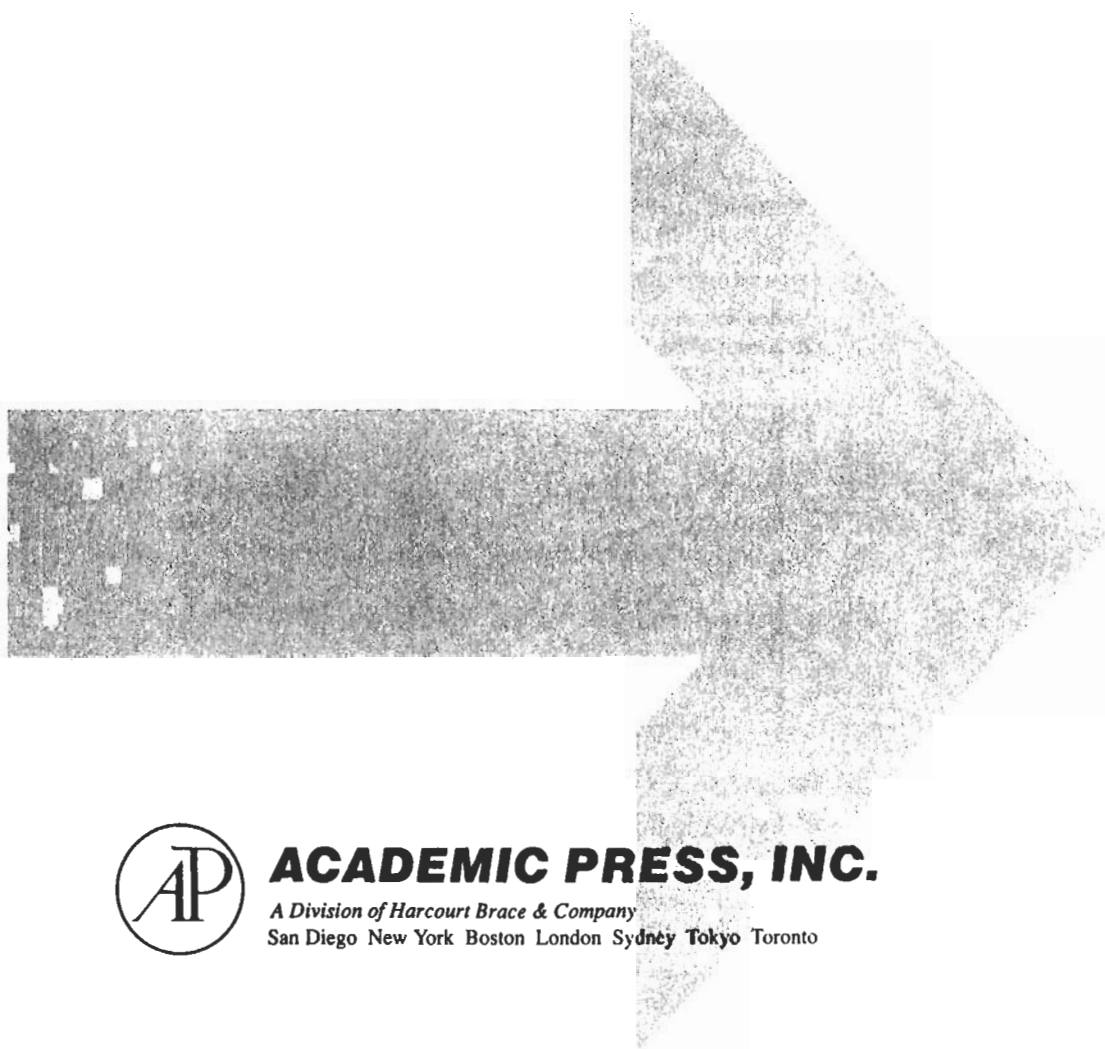
Practical Switching Power Supply Design

Marty Brown
Motorola Semiconductor



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Preface

In the age of specialization for electronics engineers, it becomes very difficult to maintain a level of competence within a broad range of electronics fields. Nonetheless, many engineers will be assigned design projects outside their primary field of expertise, among which are switching power supplies. This is done primarily because the engineer has a unique ability to learn technical subjects relatively quickly. Unfortunately, the literature available today on the subject of switching power supplies tries to convey an understanding through lengthy derivations of applied mathematics. This does not work since only an intuitive sense of the subject matter creates an understanding of the fundamental relationships.

This book is written for just this purpose. It contains *no* mathematical derivations. Instead, it contains written explanations in semitechnical terms, on such topics as magnetic behavior and feedback compensation, to give the reader a good intuitive understanding of the operation of a switching regulator. The material highlights the areas that have a strong bearing on the supply's reliable operation that are not obvious from the "paper design." It also attempts to tie together the often oblique and unrelated information presented in component manufacturer's catalogs. The design examples are written in a clear step-by-step fashion in order to show the reader the steps necessary in a typical switching regulator design. They were also chosen because of their utility in a wide range of typical applications. They can be easily modified and scaled to fit many more applications. The topics contained in the book range from considerations in capacitor and semiconductor selection to quasi-resonant converter design.

This book has been written as a result of many years of learning about switching power supplies from experience and equally many years of

frustration with the available technical resources. The material is organized specifically to answer those questions that I and the many engineers with whom I have conversed have had when faced with a switching power supply design. In short, this material is written *for* a working engineer *by* a working engineer.

1

Why Use Switching Power Supplies?

The choice of whether to use a switching or linear power supply in a particular design is significantly based on the needs of the application itself. Both linear and switching supplies have distinct merits in certain areas of application. So in order to use the more appropriate power supply type in a particular design, it is necessary to understand the cost and electrical requirements of the entire product and select the type of power supply that best satisfies those requirements.

The linear power supply offers the designer three major advantages. The first advantage is its simplicity. One can purchase an entire linear regulator in a package and simply add two filter capacitors for storage and stability. Even if the designer had to design a linear regulator from scratch, the present technology is sufficiently mature to allow duplication of a design from a book with very little effort. The second major advantage is its quiet operation and load-handling capability. The linear regulator generates little or no electrical noise on its output, and its dynamic load response time—the time it takes to respond to changes in the load current—is very short. The third advantage is that, for an output power of less than approximately 10 W, its component costs and manufacturing costs are less than the comparable switching regulator.

The disadvantages of the linear-type regulator are what limit its range of application. The designer cannot eliminate these shortcomings but can attempt to minimize their effects. First, it can be used only as a step-down regulator, which means that the designer must somehow develop an input voltage that is at least 2 to 3 V higher than the required output voltage. This means that in off-line situations a 50–60-Hz transformer with rectification and filtering must be placed before the linear power supply. This pre-power conditioning increases the system cost. Second, each linear regulator can have only one output. So for each additional

output voltage required, an entire separate linear regulator must be added. This requirement for multiple voltages once again drives up the system cost. Another major disadvantage is the average efficiency of linear regulators. In normal applications, linear regulators exhibit efficiencies of 30 to 60 percent. This means that for every watt delivered to the load, more than one watt is lost within the supply. This loss, called the *headroom loss*, occurs in the pass transistor and is, unfortunately, necessary to develop the needed biases within the supply required for operation and varies greatly when the input voltage varies between its high- and low-line specifications. This makes it necessary to add heat-sinking to the pass transistor that will be sufficient to handle the lost power at the highest specified input voltage and the highest specified load current. Most of the time the supply will not be operating under these circumstances, which means that the heatsink will be oversized during most of its operating life. This once again is an added system cost. The point where the heatsink cost begins to become prohibitive is about 10 W of output power. Up to this point, any convenient metal structural member can adequately dissipate the heat. These shortcomings greatly escalate at higher output power levels and quickly make the switching regulator a better choice.

The switching regulator circumvents all of the linear regulator's shortcomings. First, the switching supply exhibits efficiencies of 68 to 90 percent regardless of the input voltage, thus drastically reducing the size requirement of the heatsink and hence its cost. The power transistors within the switching supply operate at their most efficient points of operation: saturation and cutoff. This means that the power transistors can deliver many times their power rating to the load and the less expensive, lower-power packages can be used. Since the input voltage is chopped into an AC waveform and placed into a magnetic element, additional windings can be added to provide for more than one output voltage. The incremental additional cost of each added output is very small compared to the entire supply cost—and in the case of transformer-isolated switching supplies, the output voltages are independent of the input voltage. This means that the input voltage can vary above and/or below the level of the output voltages without affecting the operation of the supply. The last major advantages are its size and cost at the higher output power levels. Since their frequency of operation is very much greater than the 50–60 Hz line frequency, the magnetic and capacitive elements used for energy storage are much smaller and the cost to build the switching supply becomes less than the linear supply at the higher power levels.

All of these advantages make the switching power supply a much more versatile choice, with a wider range of applications, than the linear supply.

The disadvantages of the switching supply are minor and usually can be overcome by the designer. First, the switching supply is more complicated than the comparable linear supply. If a switching supply cannot be bought off-the-shelf to suit the needs of the product, then it must be designed. At this point the time it takes to design a reliable switching supply to suit one's needs can be quite sizable, and if this is the first power supply design undertaken by the designer, the learning curve can add significantly to this time. Don't be lulled into believing that the design is "cookbook." Many more considerations must be taken into account even if there is a published design that will meet the needs of the product. The experienced power supply designer will need a minimum of three worker-months, depending on its complexity, to design, prototype, and test the supply before releasing it to production. It is safe to plan on 4 to 6 worker-months' worth of effort to perfect the design prior to production. Obviously this design effort comes at a cost, and this must be considered during the product planning stage of the program. Second, considerable noise from the switching supply is generated on its outputs and input and radiated into the environment. This can be difficult to control and certainly cannot be ignored during the design phase. A little knowledge of radio-frequency (RF) behavior and design can go a long way in aiding the engineer during the design phase. There can be simple solutions to this problem, but generally additional filtering and shielding will have to be added to the supply to limit the effects of the noise on the load and the environment. This, of course, adds cost to the supply. Third, since the switching supply chops the input voltage into time-limited pulses of energy, the time it takes the supply to respond to changes in the load and the input is slower than the linear power supply. This is called *transient response time*. To compensate for this sluggishness, the output filter capacitors usually must be increased in value to store the energy needed by the load during the time the switching supply is adjusting its power throughput. Once again added cost is incurred, but note that all of these disadvantages are under the control of the designer and their impact on the supply and the system can be minimized.

Generally, the industry has settled into areas where linear and switching power supplies are applied. Linear supplies are chosen for low-power, board-level regulation where the power distribution system

within the product is highly variable and the load's supply voltage needs are restricted. They are also used in circuits where a quiet supply voltage is necessary, such as analog, audio, or interface circuits. They are also used where a low overhead cost is required and heat generation is not a problem. Switching power supplies are used in situations where a high supply efficiency is necessary and the dissipation of heat presents a problem, such as battery-powered and handheld applications where battery life and internal and external temperatures are important. Off-line supplies are also typically switchers because of their efficiency in generating all the voltages needed within the product, especially in very-high-power applications, up to many kilowatts.

In summary, because of its versatility, efficiency, size, and cost, the switching power supply is preferred in most applications. The advances in component technology and novel topological design approaches will only add to the desirability of the switching power supply in most applications.

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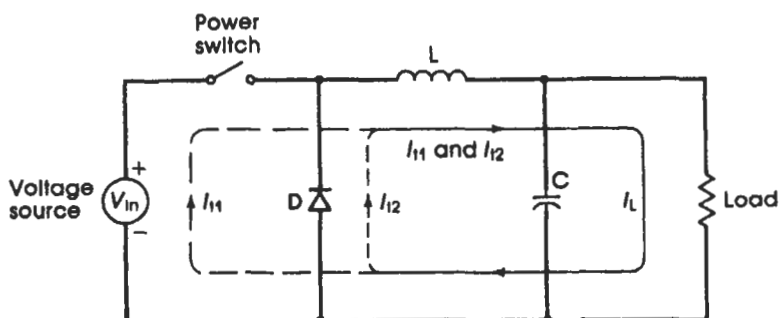
How a Switching Power Supply Works

Conceptually, switching regulators are not difficult to understand. When viewed as a blackbox with input and output terminals, the behavior of a switching regulator is identical to that of a linear regulator. The fundamental difference is that a linear regulator regulates a continuous flow of current from the input to the load in order to maintain a constant load voltage. The switching regulator regulates this same current flow by chopping up the input voltage and controlling the average current by means of the duty cycle. When a higher load current is required by the load, the percentage of on-time is increased to accommodate the change.

Two basic types of switching regulators constitute the foundation of all of the pulsewidth-modulated (PWM) switching regulators. These types are the forward-mode regulators and the flyback-mode regulators. The name of each type is derived from the way the magnetic elements are used within the regulator. Although they may resemble each other schematically, they operate in quite different fashions.

2.1 Forward-Mode Switching Regulators

Forward-mode switching regulators have as their functional components four elements: a power switch for creating the PWM waveform, a rectifier (or catch diode), a series inductor, and a capacitor (see Fig. 2.1). The power switch may be a power transistor or a metal oxide semiconductor field-effect transistor (MOSFET) placed directly between the input voltage and the filter section. In between the power switch and the filter section there may be a transformer for stepping up or down the input voltage as in transformer-isolated forward regulators. The shunt diode, series inductor, and shunt capacitor form an energy storage res-

**Figure 2.1**

Forward regulator and its current flow.

ervoir whose purpose is to store enough energy to maintain the load voltage and current over the entire off-time of the power switch. The power switch serves only to replenish the energy lost to the load during its off-time. Its function can be seen as an electrical equivalent of a mechanical piston–flywheel combination. The piston provides a pulse of energy, and the flywheel stores the mechanical energy for use by the load.

The operation of the power switch can be broken up into two periods. The first is when the power switch is on. During this period, the load current passes from the input source, through the inductor to the load, and back again through the return (or ground) lines to the input source. During this time the diode is reverse-biased. After the power switch turns off, the inductor still expects current to flow through it. The former current path through the input source is now open-circuited, and the catch diode now begins to conduct, thus maintaining a closed current loop through the load. When the power switch once again turns on, the voltage presented to the filter serves to turn off the catch diode. In short, forward current is always flowing through the inductor; hence its name.

The amount of energy being delivered to the load is controlled by the duty cycle of the power switch on-time. This may vary anywhere between 0 and 100 percent duty cycle but typically falls between 5 and 95 percent duty cycle. An approximate model of the relationship between input voltage, duty cycle, and output voltage is that the output voltage is the average of the area under the chopped voltage waveform or

$$V_{\text{out}} \cong V_{\text{in}} \cdot \text{duty cycle} \quad (2.1)$$

In reality this relationship applies only for light loads, but it does serve as a reasonable approximation elsewhere.

2.2 Flyback-Mode Switching Regulators

Flyback-mode switching regulators have the same four basic elements as the forward-mode regulators except that they have been subtly rearranged (see Fig. 2.2). Now the inductor is placed directly between the input source and the power switch. The anode lead of the rectifier is placed on the node where the power switch and inductor are connected, and the capacitor is placed between the rectifier output (cathode) and ground (return).

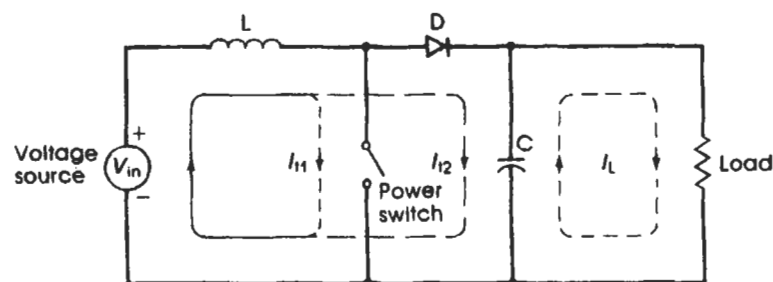
The flyback's operation can be broken up into two periods. When the power switch is on, current is being drawn through the inductor, which causes energy to be stored within its core material. The power switch then turns off. Since the current through an inductor cannot change instantaneously, the inductor voltage reverses (or flies back). This causes the rectifier to turn on, thus dumping the inductor's energy into the capacitor. This continues until all the energy stored in the inductor during the previous half-cycle is emptied. Since the inductor voltage flies back above the input voltage, the voltage that appears on the output capacitor is higher than the input voltage. Note that the only storage for the load is the output filter capacitor. This makes the output ripple voltage of flyback converters worse than their forward-mode counterparts.

The duty cycle in an elementary flyback-mode supply is 0 to 50 percent. This restriction is due to the time required to empty the inductor's flux into the output capacitor. Duty cycles within transformer-isolated flyback regulators can sometimes be larger because of the effects of the turns ratio and the inductances of the primary and the secondary.

The relationship of the output voltage to the input voltage is slightly more difficult to describe. During the power switch's off-time, the in-

Figure 2.2

Flyback-mode regulator and its current flow.



ductor will empty itself before the start of the next power switch conduction cycle. Since the volt-time products of the inductor charging and discharging cycles must be equal and the output for a nonisolated “boost” converter must be higher than the input voltage, the resulting relationship is

$$V_{\text{out}} \cong V_{\text{in}} + V_{\text{fbk}} \cong V_{\text{in}} \left(1 + \frac{T_{\text{on}}}{T_{\text{fbk}}} \right) \quad (2.2)$$

At the minimum operating voltage, the duty cycle reaches 50 percent and T_{fbk} equals the total operating period minus the “on-time.”

3

A Walk through a Representative Switching Power Supply

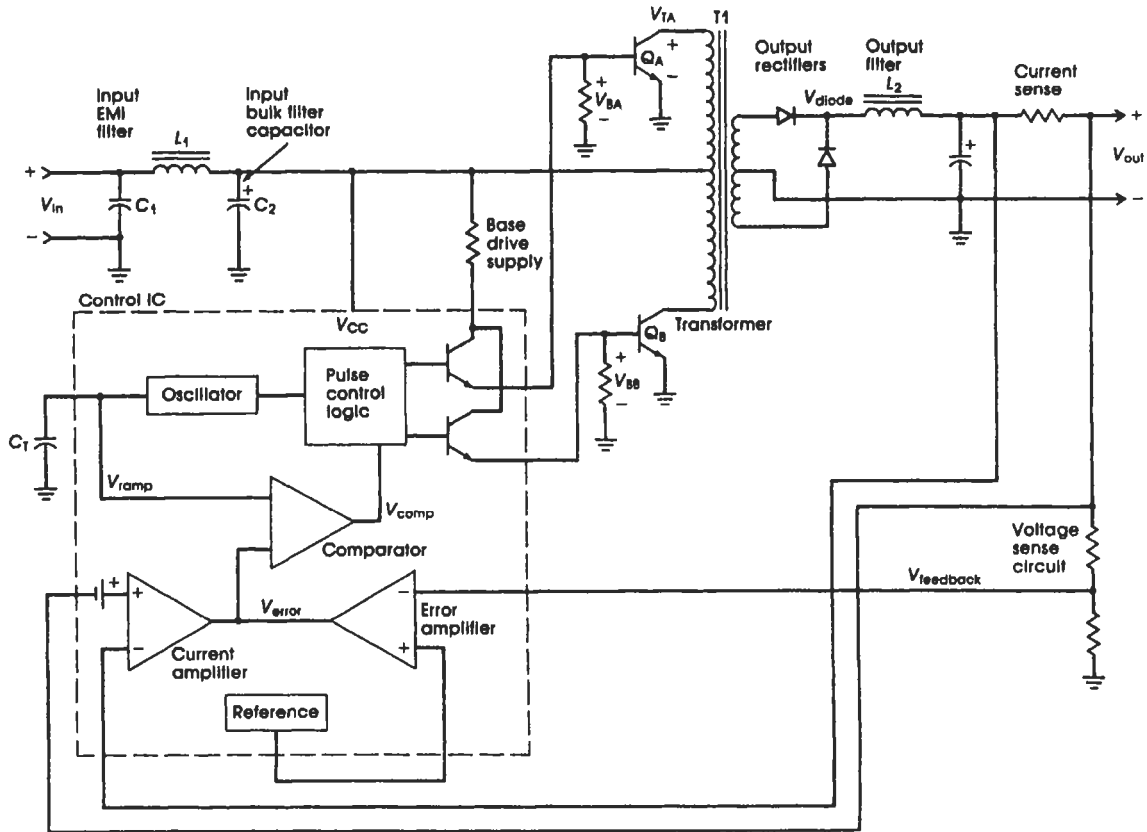
In order to adequately approach a switching power supply design, the designer must have a reasonable understanding of the major subsections that make up a switching power supply. The subsections discussed represent a typical minimum system. Additional functionality may be added to the supply by adding to these basic subsections. The supply discussed is a single output, push-pull regulator. The circuit sections and waveforms are shown in Figures 3.1 and 3.2.

3.1 The EMI Filter

This section is composed of a small L - C filter between the input line and the regulator. It serves a dual purpose. First, C_1 and L_1 act as a high frequency radio-frequency interference (RFI) filter, which reduces the conducted high frequency noise components leaving the switching supply back into the input line. These noise currents would then radiate from the input power lines as in an antenna. The lowpass cutoff frequency of this filter should be no higher than 2 to 3 times the supply's operating frequency. The second purpose of this stage is to add a small impedance (L_1) between the input line and the bulk input capacitor. It basically reduces any lethal transient voltage and allows the bulk input filter capacitor and any surge protector to absorb the destructive energies from the input line spikes or surges with little chance of exceeding any of the components' voltage ratings.

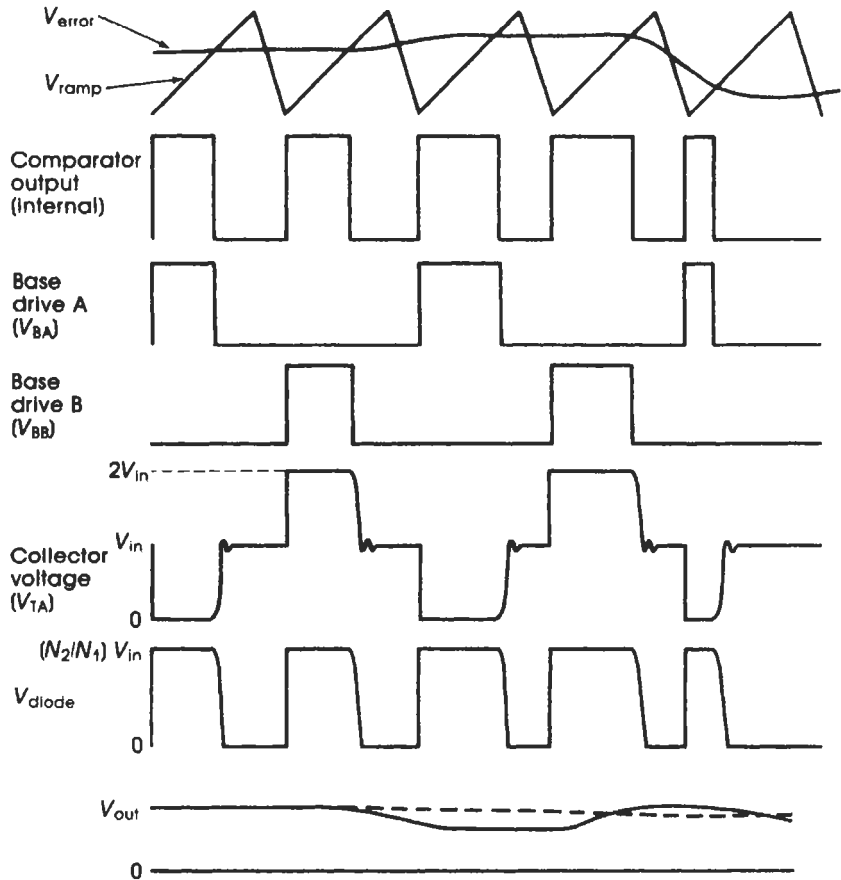
3.2 Bulk Input Filter (Storage) Capacitor

This capacitor is relatively large in value. It has the responsibility of storing the high- and low-frequency energy required by the supply dur-

**Figure 3.1**

A walk through a representative switching regulator circuit.

ing each power transistor's conduction cycle. It is usually made up of at least two capacitors, an electrolytic or tantalum capacitor for the current components at the supply's switching frequency and a ceramic capacitor for the switching frequency harmonics. This capacitance must represent a low impedance from direct current (DC) to many times the switching frequency of the supply. Another factor that necessitates the use of the bulk input capacitor is that the input line may have long lengths of wire or printed circuit board trace, which adds series resistance and inductance between the power source and the supply. The input line at high frequencies actually resembles a current-limited current source and cannot deliver the high-frequency current demands of the supply necessary for the fast voltage and current transitions within the supply. The input capacitor charges at a low frequency and sources current over a much higher frequency range. Without both a low-frequency electrolyte-

**Figure 3.2**

Representative waveforms.

type capacitor and a high-frequency ceramic-type capacitor, the supply would starve for high-frequency current and voltage and adversely affect the supply's stability.

3.3 Transformer

In this configuration, the transformer provides DC isolation between the input line and the output. It also performs a voltage step-up and/or step-down function for the supply. The transformer does not store energy in this configuration. Additional outputs may be added by simply adding another winding on the secondary. This allows one switching supply to provide all the voltages required by most product designs. The transformer is also the backbone of the switching power supply. If the trans-

former is improperly designed, it would adversely affect the supply operation and the reliability of the semiconductors.

3.4 Power Switches

These are power transistors or MOSFETs that are quickly switched between the saturation (full-on) and the cutoff (full-off) states. They serve as a “gate” for the energy entering the supply that is subsequently delivered to the load. The energy flow is regulated by the control circuit, which senses the energy demanded by the load and then varies the percentage of on-time for the power switches, which then “regulate” the delivery of the energy to the load to match the load’s demands. The power switches also represent the least reliable components within the supply. If any components are to fail during an adverse operating condition, these would be the first ones to fail. So great care should be taken during the design and selection phase to ensure their reliable performance.

3.5 Output Rectifiers

In this regulator configuration, the output rectifiers conduct at the same time as the power switches. The secondary voltage waveforms in isolated configurations such as this have an average DC value of zero (centered about 0 V), but during the on-time of the power switches the secondary voltage reaches peak values of the turns ratio times the input voltage. The rectifiers convert this bipolar waveform into a unipolar pulse train. To change the polarity of the output voltage, one simply reverses the rectifier’s polarity. Although the rectifier conducts an average current equal to the load current, the peak value of the current will be higher than the average. So during the rectifier selection process the designer should consider any additional losses incurred during these high peak currents and add a margin to the current specification.

3.6 The Output Filter Section

This is an example of the output filter section of a forward-mode converter. This filter is called a *choke input filter* (or *LC filter*) and is a

series inductor followed by a shunt capacitor. Its purpose is to store energy for the load during the times when the power switches are not conducting. It basically operates like an electrical equivalent of a mechanical flywheel. The on-time of the power switches serves only to replenish the energy lost by the inductor during their off-time. Typically, approximately 50 percent more energy is stored in the inductor and capacitor than is needed by the load over the entire period. This reserve can be drawn on by sudden increases in load demand until the control loop can provide more energy by increasing the on-time of the power switches.

3.7 Current Sense Elements

The method shown here is only one way of implementing the overcurrent sensing function. Essentially, the purpose is to develop a voltage that is proportional to the output load current. This voltage is then amplified, and if it becomes too high (an overcurrent condition), it overrides the voltage regulator control loop and forces a reduction in the output voltage. Depending on the way the output current is sensed, what other parameters are summed in, and the gain of the current-sensing amplifier, one can either achieve a constant power limiting, a constant current limiting, or a current foldback limiting. The type of limiting chosen depends on how much power the load can withstand during an overcurrent or short-circuit failure. In voltage-mode regulators this feature remains completely inactive until an abnormal overcurrent condition is entered. In current-mode control regulators, the transformer's primary current is sensed and used as part of the overall control strategy of the supply, offering not only overcurrent protection but also improved supply responsiveness.

3.8 Voltage Feedback Elements

This is usually a resistor divider, which reduces the rated output voltage to the same voltage appearing as the reference voltage on the input to the voltage error amplifier. The voltage error amplifier amplifies the difference between the ideal level—dictated by the reference voltage—and the actual output voltage as presented by the feedback elements and controls the on-time of the power switches accordingly.

3.9 The Control Section

This function is typically centered around a switching power supply control integrated circuit. It performs the functions of DC output voltage sensing and correction, voltage-to-pulsewidth conversion, a stable reference voltage, an oscillator, overcurrent detection and override, and the power switch driver(s). It may also include a soft-start circuit, dead-time limiting, and a remote shutdown. The oscillator sets the frequency of operation of the supply and generates a sawtooth waveform for the DC-to-pulsewidth converter. The voltage error amplifier amplifies the difference between the “ideal” reference voltage and the sensed output voltage presented by the resistor divider feedback elements. The error amplifier’s output voltage represents this error between the reference and the actual output multiplied by the high DC gain of the operational amplifier riding on a DC offset. This error signal is then presented to the DC-to-pulsewidth converter, which produces a pulsetrain whose duty cycle represents this error signal. This pulsetrain is then presented to the power switch driver(s). If the supply is single-ended, that is, has only one power switch, the waveform is used to drive the output driver directly. If it is a double-ended supply (two power switches), this pulsetrain is first placed into a digital flip-flop that steers the pulses alternately between two output drivers. The output drivers themselves usually take one of two forms. First is the uncommitted transistor, which is where both the emitter and collector of the output transistor are brought out of the integrated circuit (IC) and are better suited for driving bipolar power transistor power switches. The second type is the push–pull driver. This type is preferred for driving power MOSFETs. These control functions represent the minimum functionality of a control IC.

Added functionality, which varies from IC to IC, should be considered carefully, keeping in mind the system design. This might include soft-start, remote shutdown, and synchronization. Soft-start reduces the inrush current into the supply during startup by overriding the error amplifier and hard-limiting the initial maximum pulsewidths until the supply has reached its desired output. Remote shutdown is a circuit that inhibits supply operation electrically by shutting down the control functions without removing power to the power sections of the supply. This feature is intended for those applications where it is impractical to interrupt the supply’s high-current input line. Synchronization is needed for those systems having sections where the fixed frequency output ripple of the power supply would interfere with a critical system circuit such as a

cathode-ray-tube display or an analog-to-digital or digital-to-analog converter. In those cases the conduction pulses would be synchronized in phase and frequency to the critical circuit and could be placed in phase such that the critical circuit would be immune to the supply's ripple voltage. It also may be necessary to synchronize more than one switching power supply. The designer must study each control IC carefully in order to select the most appropriate IC for the application.

These basic functional subsections represent the minimum functionality that a typical switching power supply should possess. Additional functions that may or should be added are input transient protection, undervoltage lockout, output overvoltage protection, and any power sequencing that the supply may need to provide to the system. Many items need to be considered at the system design specification stage of a system development program and should be discussed as early in the program as possible. This will aid the designer in outlining the best possible design approach to the switching power supply and avoid any last minute design changes downstream in the program.

4

Switching Power Supply Topologies

Switching power supplies gained popularity in the early 1970s, coinciding with the introduction of the bipolar power transistor. The basic theory of the switching power supply has been known since the 1930s. Since the 1930s, many evolutionary changes have occurred to make the switching power supply meet the needs of many diverse applications. For this reason, many variations have evolved, each with merits that make it better suited for particular applications. Some topologies work better at high input voltages, some at higher output power levels, and some are targeted for the lowest cost. Keep in mind that many topologies can work for each particular application, but one topology usually has the right combination of features that makes it the best choice.

4.1 Factors Affecting the Choice of an Appropriate Topology

In order to select an appropriate topology for your application it is necessary to understand the subtle differences between the topologies and what factors make them more desirable for certain applications. Five primary factors differentiate the various topologies from one another:

1. *The peak primary current.* This is an indication of how much stress the power semiconductors must withstand and tends to limit a particular configuration in the output power it can deliver and the input voltage over which it can operate.
2. *How much of the input voltage can be placed across the primary winding of the transformer.* This indicates how effectively power can be derived from the input line. Switching power supplies are constant-power circuits, so the more voltage supplied to the trans-

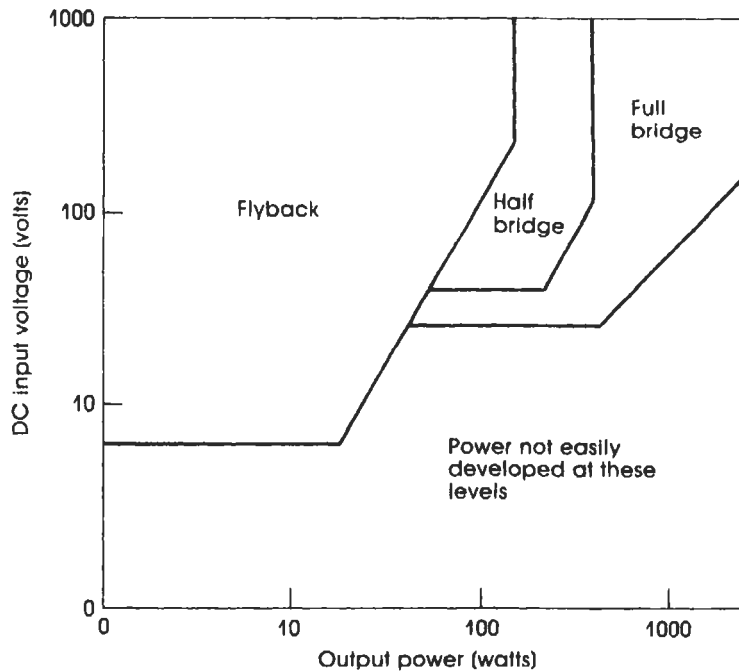
former or inductor, the less the average and peak currents needed in order to develop the output power.

3. *How much of the B–H characteristic can be used within the transformer during each cycle.* This indicates which configurations have physically smaller transformers for a rated output power.
4. *DC isolation of the input from the load.* This provides DC isolation of the output from the input and allows the designer to add multiple outputs with ease. Transformer isolation may also be necessary in order to meet the safety requirements dictated by the marketplace.
5. *Cost and reliability.* The designer wishes to select a configuration that requires the minimum parts without subjecting the components to undue overstress.

At the beginning of each power supply design effort the designer should perform a little predesign estimation exercise. This is done by making a reasonable assumption about the supply efficiency and working with the general equations involving the peak currents and voltages. From this exercise, one can select the best switching power supply topology, select the preliminary choices for the semiconductors, and even estimate the amount of losses within the components. It may also guide the designer in an approach to packaging the power supply and provide some idea as to the final cost of the supply. This effort can act as an early roadmap during the design phase and also saves time because the designer can order the semiconductor components before the power supply is even designed.

The industry has settled into several primary topologies for a majority of the applications. Figure 4.1 diagrams the approximate range of usage for these topologies. The boundaries to these areas are determined primarily by the amount of stress the power switches (power transistors or MOSFETs) must endure and still provide reliable performance. The boundaries delineated in Figure 4.1 represent approximately 20 A of peak current. Higher peak currents can be used but the power switches would begin to exhibit unusual failure modes, and items such as board layout and lead lengths would become even more critical. It is also no coincidence that these topologies are transformer-isolated topologies. The non-transformer-isolated topologies have very predictable and catastrophic failure modes that most experienced switching power supply designers prefer not to risk.

The flyback configuration is used predominantly for low to medium output power (<150 W) applications because of its simplicity and low

**Figure 4.1**

Industry favorite configurations and their areas of usage.

cost. Unfortunately, the flyback topology exhibits much higher peak currents than do the forward-mode supplies, so at the higher output powers, it quickly becomes an unsuitable choice. For medium-power applications (100 to 400 W) the half-bridge topology becomes the predominant choice. The half-bridge is more complicated than the flyback and therefore costs more, but its peak currents are about one-third to one-half those exhibited by the flyback. Above 400 W, the peak currents once again become very high and it becomes unsuitable. This is because the half-bridge does not effectively utilize the full power capacity of the input source. Above 400 W the dominant topology is the full-bridge topology, which offers the most effective utilization of the full capacity of the input power source. It also is the most expensive to build, but for those power levels the additional cost becomes a trivial matter. Another topology that is sometimes used above 150 W is the push-pull topology, which exhibits some fundamental shortcomings that make it tricky to use.

By using Figure 4.1 and estimating the major power supply parameters as a preliminary guide at the beginning of a switching power supply

design effort, one can be reasonably sure that the final choice of topology will provide a reliable and cost-effective design.

4.2 Non-Transformer-Isolated Switching Power Supply Topologies

The non-transformer-isolated type of switching power supplies are typically used when some external component provides the DC isolation or protection in place of the switching supply. These external components are usually 50–60-Hz transformers or isolated bulk power supplies. Their typical area of application is in local board-level voltage regulation. The non-transformer-isolated supplies are also easy to understand and thus are used as design examples by various manufacturers and subsequently overused by novice power supply designers. Nonisolated-type configurations seldom are used by seasoned power supply designers simply because of the severity of the failure modes caused by the lack of the DC isolation. Also, isolated supplies add a degree of safety by having a second DC dielectric barrier to back up the 50–60-Hz transformer, which enhances the supply's degree of graceful degradation during any possible failures.

There are three basic non-transformer-isolated topologies: the buck (step-down), the boost (step-up), and the buck–boost (inverting). Each topology generates and regulates an output voltage that is above or below the input voltage. Each also has only one output since it is not very practical to add additional outputs to them. Non-transformer-isolated supplies also have definite restrictions as to their application in regard to their input voltage with respect to their output voltage. The designer should consider these factors prior to the use of a nonisolated topology.

4.2.1 The Buck Regulator Topology

The buck regulator is the simplest of all the switching power supply topologies. It is also the easiest to understand and design. The buck regulator is also the most elementary forward-mode regulator and is the basic building block for all the forward-mode topologies. The buck regulator, though, exhibits the most severe destructive failure mode of all the configurations. For this reason, it should be used only with extreme discretion.

The buck regulator's basic operation can be seen as roughly analogous to a piston–flywheel combination. A steady-state DC current whose average value equals the output load current is always flowing through the inductor. The power switch, a power MOSFET in this case, acts only to replenish the energy in the inductor that was removed by the load during the MOSFET's off-time. The diode, called a *commutating diode*, maintains the flow of the load current through the inductor when the power switch is turned off. There are two current paths inside a buck regulator. When the power switch is conducting, the current is passed through the input source, the power switch, the inductor, and the load, after which it returns to the input source. Since the input source can provide much more energy than the load wants, the excess is stored in the inductor. When the power switch is off, the load current is passed through the commutation diode to the load and back again. The energy behind the sustained current flow is provided by the excess energy stored in the inductor, which is now being drawn on. This continues until the power switch is once again turned on and the cycle starts over again.

The voltage and current waveforms are shown in Figure 4.2. Analytically, they are quite easy to describe. First, the commutating diode's voltage is

$$V_d(Q_{on}) = V_{in} - V_{sat} \quad (\text{input voltage less the saturation drop of the power switch})$$

$$V_d(Q_{off}) = -V_{fwd} \quad (\text{the forward voltage drop of the diode})$$

The inductor's current can be seen as

$$Q_{on}: \quad I(\text{induct}) = I_{min} + \frac{[(V_{in} - V_{sat}) - V_{out}] T_{on}}{L}$$

$$Q_{off}: \quad I(\text{induct}) = I_{pk} - \frac{(V_{out} + V_{fwd}) T_{off}}{L}$$

This yields a nice triangular current waveform whose edges are linear ramps. The inductor current is the sum of the power switch's and diode's current waveform. They are positive and negative ramps, respectively, riding on a current pedestal. The pedestal is indicative of the residual energy stored within the inductor acting as an energy reservoir. The residual energy is needed to quickly respond to changes in the load current before the control circuit can respond to the change. The DC average of this current waveform is equal to the DC current being drawn by the load.

Regulation of the output voltage is accomplished by varying the duty

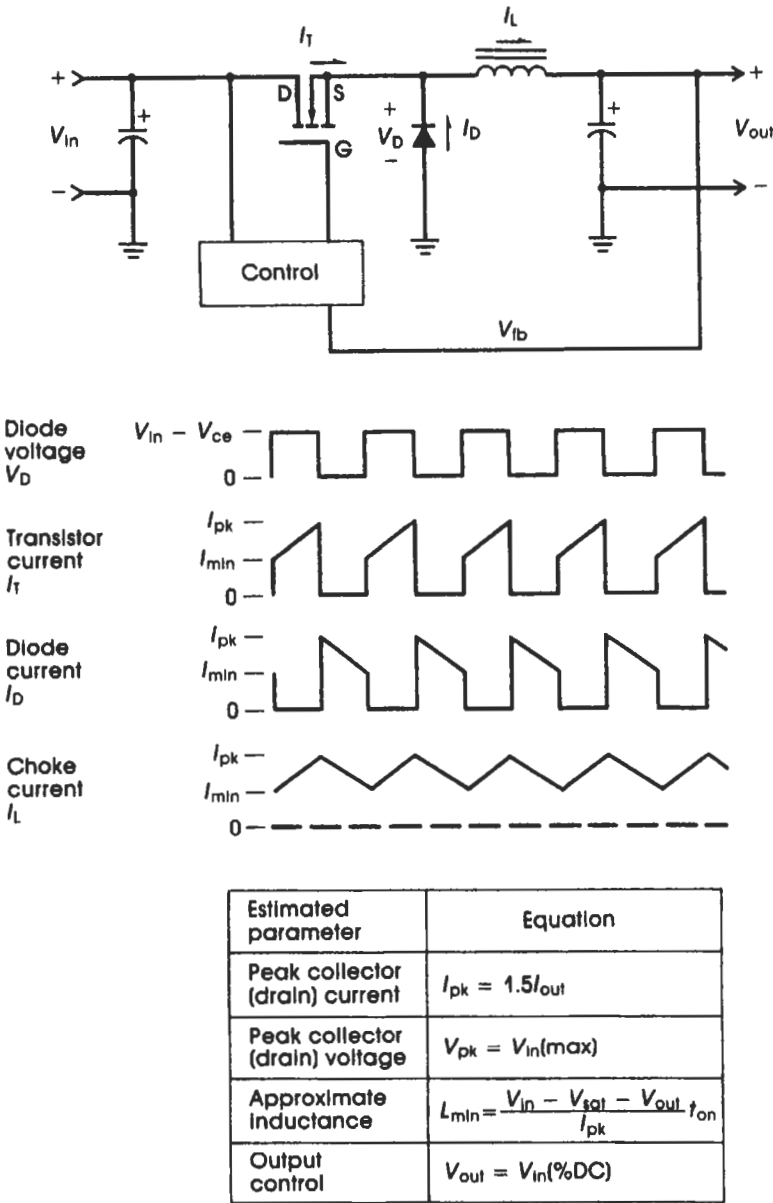


Figure 4.2
The buck regulator.

cycle of the power switch's on-time versus off-time. This yields a control equation of

$$V_{out} = V_{in} \times (\text{duty cycle}) \quad [\text{approximation}]$$

As seen from the control equation, the higher the input voltage is above the output voltage, the narrower the on-time pulsewidth of the power

switch. Conversely, the closer the input voltage gets to the output voltage, the more the duty cycle approaches 100 percent. It can also be seen that the output voltage is approximately the DC average of the power switch's output voltage waveform.

The buck regulator topology suffers from some limitations and problems imposed by the physics underlying its operation.

1. The input voltage must always be at least 1 to 2 V higher than the output voltage in order to maintain its regulated output. This can present a problem if the input supply could possibly approach the level of the output. This requirement is identical to the linear regulator where an input "headroom" voltage must be maintained for proper operation. As a result, the buck regulator can be used only as a step-down regulator.
2. When the power switch turns on, the diode is still conducting the inductor current. A diode takes a finite amount of time to assume a reverse-biased or off state, as specified by the reverse recovery time (T_{rr}) of the diode. While the diode is turning off, current will actually flow from the input line through the power switch and the diode to ground. This is actually an instantaneous short circuit across the input supply and adds stress to the power switch and diode. There is no way to eliminate this stress, but select the fastest reverse recovery diode possible (T_{rr}).
3. Semiconductor power transistors and MOSFETs almost always fail in the short-circuited condition when they do fail. This results in the input being short-circuited to the output load. Obviously, if there are no other means of protection, the output load circuitry would literally burn up. This is not a good way for a designer or a company to maintain a good reputation. The designer must add an overvoltage crowbar circuit to the output of the supply and a fuse in series with the input. The overvoltage crowbar [a silicon-controlled rectifier (SCR) driven by a voltage comparator] senses when the output voltage goes above a predetermined threshold, the SCR triggers, thus pulling an enormous current to the input ground return, which subsequently causes a series fuse to blow open. In reality the crowbar can be activated by spikes that may be asserted by the load or by a sluggish regulator in response to a rapid change in the load current. The regulator in this case enters a current foldback condition. This is an annoyance to the operator of the equipment, who must recycle (turn off and then turn on) the input power switch. The designer cannot ignore this failure mode. Component failures during the life of a product are a fact of life, so the designer should always create a design in anticipation of these events.

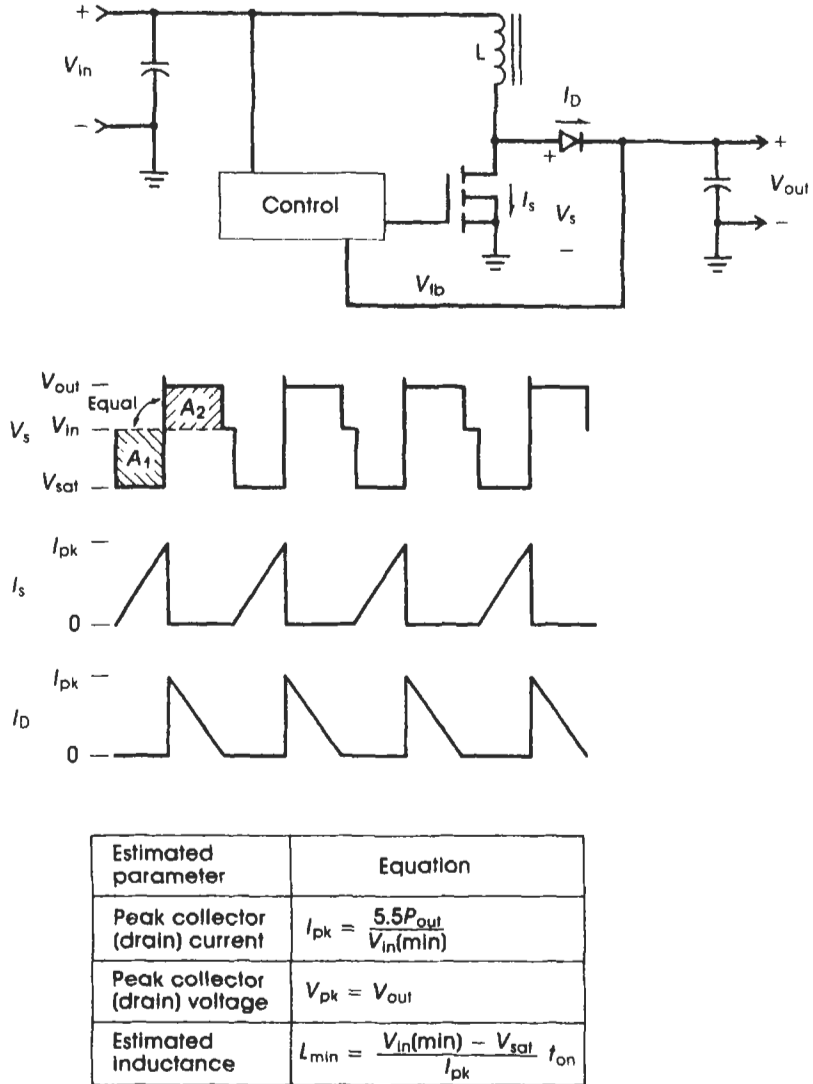
Although this topology is capable of delivering over 1000 W to a load in normal operation, it is not a popular choice among seasoned switching power supply engineers because of the above-mentioned shortcomings.

4.2.2 The Boost Regulator Topology

The boost regulator, otherwise known as a step-up regulator, is a flyback-mode topology. Its output voltage must always be higher than the input voltage.

The boost regulator uses the same number of components as the buck regulator, but they have been rearranged as seen in Figure 4.3. Its operation is also very much different from the forward-mode, buck converter. When the power switch is turned on the input voltage (V_{in}) is placed across the inductor. This causes the inductor current to linearly ramp up from 0 A until the power switch is turned off. During this time energy has been stored within the core material. At the instant the power switch is turned off the inductor voltage flies back above the input voltage. The inductor would reach an infinite voltage but is clamped to a value of the output voltage when the output rectifier becomes forward biased ($V_{out} + V_{diode}$). During the time which follows the energy within the core is emptied into the output filter capacitor and is made available to the load. This topology is limited to a 50 percent duty cycle since the core needs sufficient time to empty its energy into the output capacitor.

The mode of operation described above is referred to as the “discontinuous” mode of operation. This is the mode in which the vast majority of boost regulators operate. Its waveforms can be seen in Figure 4.3. The inductor voltage returns to zero (or V_{in} across the power switch) when the core has finished emptying its energy. The current ramp begins from zero. The other mode of operation is called the “continuous” mode. This occurs when the core cannot completely empty itself during the off-time of the power switch and some residual energy remains within the core. Now the inductor voltage does not return to zero and the current ramp rides on a pedestal that has a value proportional to the residual energy remaining in the core. Discontinuous-mode boost regulators can enter the continuous mode at low input voltages since the on-time pulsewidths grow larger in order to bring in the necessary energy required by the load. This does not allow enough time to empty the core’s energy and usually indicates that the supply will soon be falling

**Figure 4.3**

The boost regulator.

out of regulation. The boost supply can be designed to operate in the continuous mode but this presents some stability problems, as described in Chapter 10.

An important question that must be answered during the design of the boost regulator is whether or not the inductor can provide enough energy to the load for its steady-state requirements. This can be determined by knowing the basic relationships within the boost regulator. The amount

of energy stored within the core during each on period of the power switch is

$$W = \frac{1}{2} L(I_{pk} - I_{min})^2 \quad (4.1a)$$

and the average power delivered to the output is

$$P_{out} = Wf \quad (4.1b)$$

where P_{out} is the maximum output power capability of the inductor and f is the frequency of operation of the regulator. The P_{out} determined above should always be greater than the highest power needed by the load. If it is not, then the regulator will operate at light loads but will be unable to maintain regulation at the heavier loads.

So the problem is to make the inductance value low enough (but not too low as to resemble a short-circuit) to be able to accept sufficient energy at the lowest specified input voltage. This can be seen below.

$$I_{pk} = (V_{in} T_{on})/L \quad (4.1c)$$

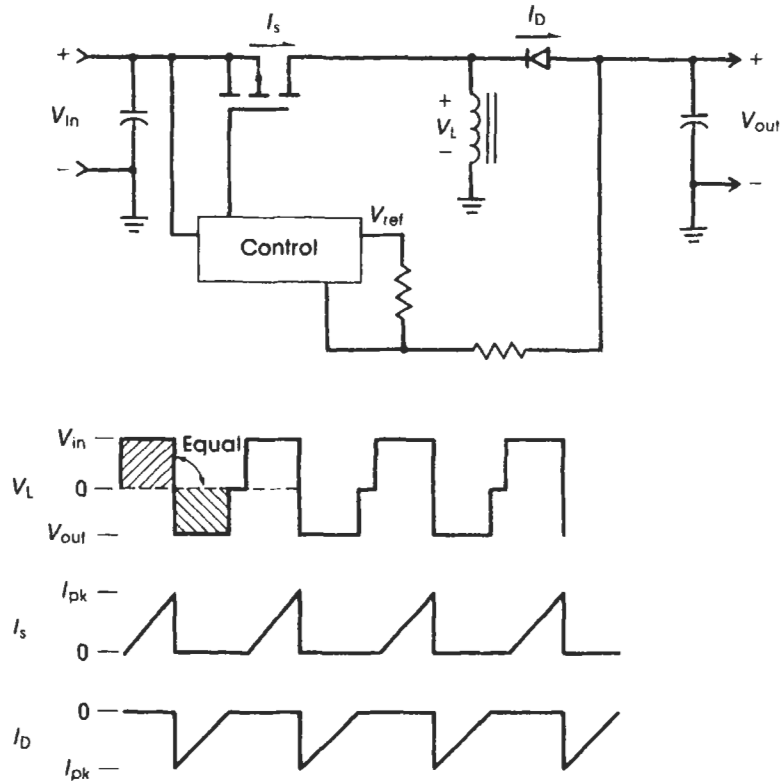
In order to maintain this energy, dictated by I_{pk} , at a low input voltage, the on-time must be increased. Soon a point is reached where the on-time pulsewidth extends into the period when the core is supposed to empty its energy into the output. Beyond this point any increase in pulsewidth only serves to add to the residual energy remaining in the core and the regulator will cease to regulate the output voltage. The designer's role is to determine the value of the inductance at which this occurs below the minimum specified input voltage.

This topology operates at about three times the peak current of forward-mode regulators. This is due mainly to having a 50 percent duty cycle limit. This high peak current limits its usefulness above 150 W since the stress on the semiconductor power switch becomes too great.

As with all non-transformer-isolated topologies, the ability of the boost regulator to prevent hazardous transients or failures within the supply from reaching the load is quite poor. For instance, if a large positive surge were to enter the regulator, it would exceed the output voltage and conduct directly into the load. Obviously, one could add transient protection, but many designers use the flyback regulator topology in place of the boost regulator. The transformer isolation vastly improves this condition.

4.2.3 The Buck–Boost Regulator Topology

The buck–boost regulator is a form of flyback-mode regulator, whose operation is very closely related to the boost regulator. It is also known



Estimated parameter	Equation	Comment
Peak collector (drain) current	$I_{pk} = \frac{5.5P_{out}}{V_{in(min)}}$	
Peak collector (drain) voltage	$V_{pk} = -(V_{in(max)} - V_{out})$	V_{out} is negative
Estimated inductance	$L_{min} = \frac{V_{in} - V_{sat}}{I_{pk}}$	

Figure 4.4

The buck-boost regulator.

as an *inverting regulator*. The difference between the boost and the buck-boost regulators, as seen in Figure 4.4, is that the positions of the power switch and the inductor have been reversed. Like the boost regulator, the inductor stores energy in the core material during the power switch's on-time. This stored energy is then released below ground (or

the input return lead) through the rectifier into the output storage capacitor. The result is a negative voltage whose level is regulated by the duty cycle of the power switch. The buck–boost regulator is also limited to below a 50 percent power switch duty cycle since it requires time to empty the core of its stored energy.

The equations related to the core and its energy requirements are identical to those of the boost regulator. Once again, the inductor must store enough energy during each cycle of operation in order to sustain the load during that same period. This is determined at the low input voltage, where the voltage across the inductor is at its lowest and hence not able to absorb as much energy per microsecond, and at the maximum rated output load. This is the worst possible point of operation where the duty cycle approaches its physical maximum of 50 percent. As in all flyback-mode regulators, to increase the rate of storage within the inductor, if the energy is insufficient as seen by the regulator falling out of regulation at low input voltages, the designer decreases the inductance of the inductor. This helps the flyback-mode regulators operate at lower input voltages, but in this situation the peak currents can become too large to ensure reliable operation of the semiconductors.

The buck–boost regulator can suffer from catastrophic failure modes similar to those of either the buck or the boost regulator separately. First, if a negative transient is allowed to enter the regulator, a bipolar power transistor power switch may avalanche (overvoltage breakdown) the reverse-biased base–collector junction, which would cause the transistor to fail. This would then allow the negative transient voltage to enter the output and place an overvoltage stress on the load. Conversely, if a large positive transient enters the regulator, any semiconductor power switch will eventually enter avalanche breakdown and once again fail, short-circuit, and subsequently cause the rectifier to enter avalanche. This would then cause the positive input voltage to be placed across circuitry that is expecting only a negative voltage. Obviously, this will cause the load to fail. The good news is that for the more common source of power switch failure, overdissipation, the rectifier does offer some means of protection by virtue of its reverse-biased condition during the times when positive voltage is on its cathode. There is a very simple solution to these failure modes: the addition of a large overvoltage zener diode across the output capacitor and a fuse or circuit breaker ahead of the supply. For negative transient breakdowns, the zener will clamp the output voltage to safe limits and will blow the fuse. For positive transient breakdowns, the zener will act like a large forward-biased diode and shunt the current to ground and blow the fuse.

As in all power supply designs, it is better to suppress any transient before it enters the supply.

Once again, this topology is not typically used by experienced power supply designers because semiconductors offer poor isolation and protection against failures and failure-inducing conditions. This topology can reasonably be used only when a transformer or transformer-isolated supply is placed between the regulator's input and the input power source. An example of where one may use the buck–boost regulator would be as a board-level local regulator within a system that has a main power supply.

4.3 Transformer-Isolated Switching Power Supply Topologies

As one may have seen in the non-transformer-isolated regulator topologies, only the semiconductors provide the DC isolation from the input to the output. Semiconductors have relatively low breakdown voltages and exhibit the worst mean time between failures (MTBF) of all the components within any given power supply. This is not because they were manufactured incorrectly but because of heat factors and sporadic adverse operating conditions such as transients. The transformer-isolated switching power supply topologies rely on a physical dielectric barrier provided by wire insulation and/or insulated tape. The energy passes through a nonconducting ferrite material prior to reaching the output. This transformer isolation can withstand many thousands of volts before it fails and does provide a second dielectric barrier in the event of a semiconductor failure. This greatly discourages the domino effect of failures once a failure does occur within the final product.

On close inspection, the transformer-isolated regulators operate analogously to the nonisolated regulators. Similarly, there are forward- and flyback-mode regulators as in the non-transformer-isolated topologies. The transformer now provides a step-up/step-down function within the supply. The transformer also provides a second great advantage, the ease of adding multiple outputs to the power supply without adding additional separate regulators for each output. All these factors make the transformer-isolated regulator topologies an attractive choice for virtually all applications.

4.3.1 The Flyback Regulator Topology

The flyback regulator topology is the only flyback-mode regulator within the transformer-isolated family of regulators. It also is the sim-

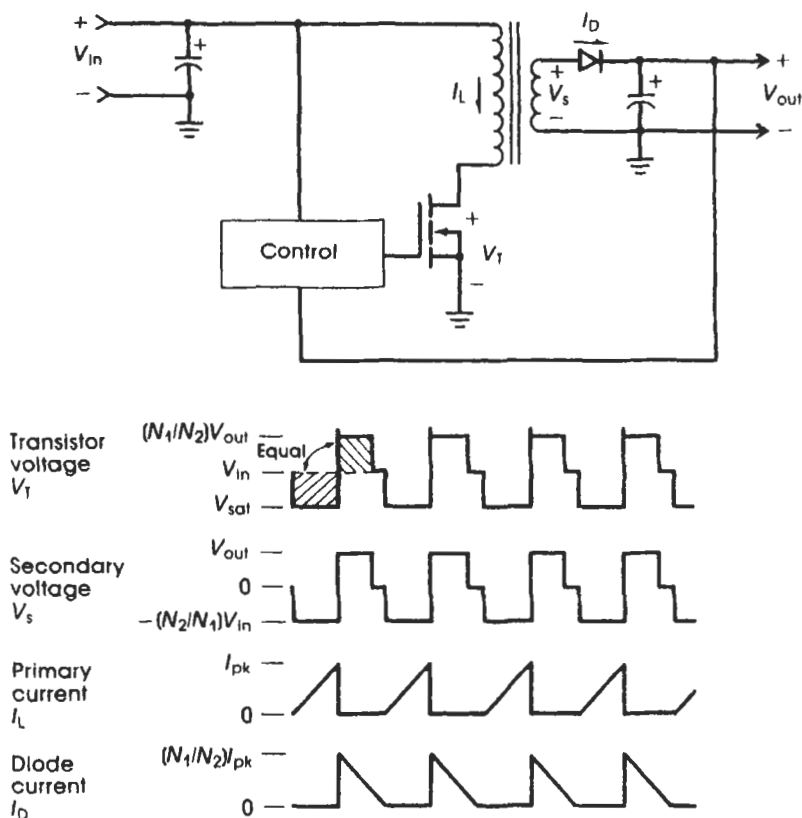
plest (contains the least parts) of all the transformer-isolated regulators. It is very closely related to the boost regulator but exhibits a great many advantages over its nonisolated counterpart. These advantages are so significant that it is selected over the boost in the vast majority of the applications.

As one may notice in Figure 4.5, the flyback design strongly resembles that of the boost regulator design except for the addition of a secondary winding on the inductor. Indeed, the size of the flyback regulator is only slightly larger than that of a boost regulator. It is the addition of this secondary winding that gives the flyback regulator its versatility. The advantages of the flyback over the boost or the buck–boost regulators are as follows.

1. More than one output is possible on one supply.
2. These outputs can be positive or negative in voltage.
3. The output voltage levels are independent of the input voltage.
4. The input voltage exhibits high dielectric isolation from the input to the output.

The flyback regulator actually works as a boost and a buck–boost regulator combined, and the input voltage can traverse the levels of any of the output voltages without affecting the operation of the supply.

The operation of the flyback regulator can be discussed by breaking one period of operation into two parts: the power switch's on-time and off-time. During the on-time, the full input voltage is placed across the primary winding of the transformer. This results in an increasing linear current ramp through the primary whose slope is $+V_{in}/L_{pri}$. This continues until the power switch is turned off. At this point the voltage as measured across the power switch (a MOSFET in this case) flies back to a voltage equal to the sum of the input voltage plus the turns ratio multiplied by the output voltage (plus a diode drop). So for example, if the transformer had a 1 : 1 turns ratio with a 5-V output, the flyback voltage would be 6 V above the input voltage (5 V + 1 V for the diode). During the flyback period (the power switch off-time) the output rectifier conducts, thereby passing the stored energy within the core material to the output capacitor and the load. This flyback period continues until either the core is depleted of energy, after which the power switch's voltage returns to the voltage of the input, or the power switch is once again turned on. The secondary current during the flyback period is a declining linear ramp with a slope of $-V_{out}/L_{sec}$. As one can see, since input and output voltages are rarely, if ever, equal and the primary and secondary turns may not be equal, the power switch on-time and the



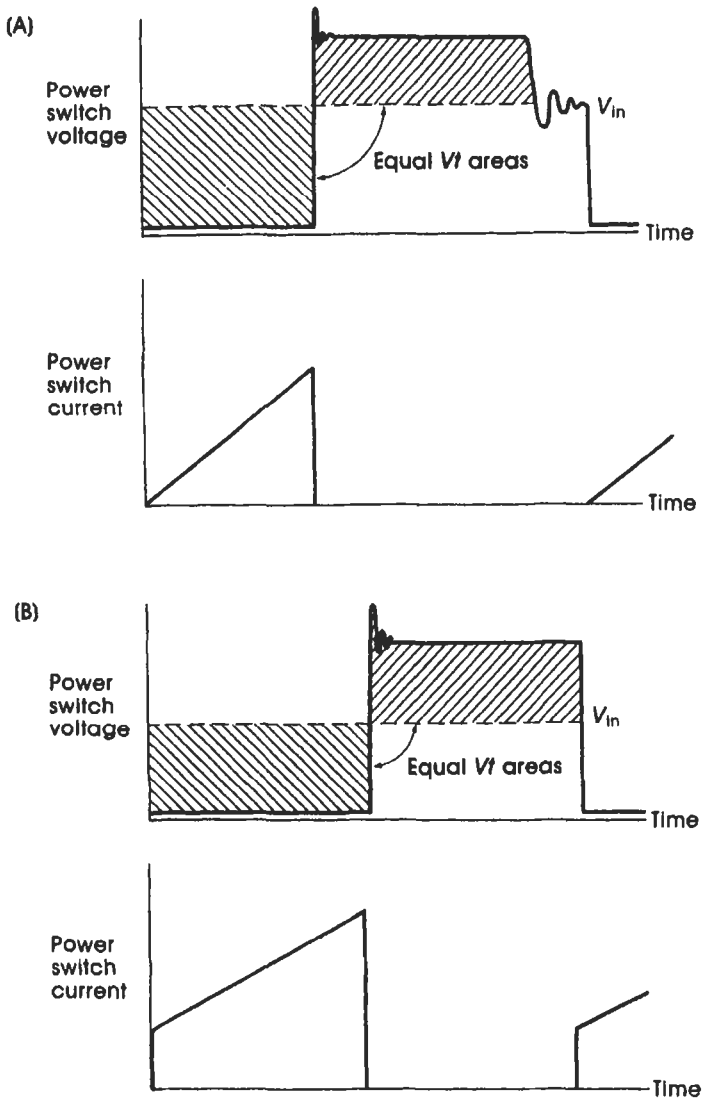
Estimated parameter	Equation
Peak collector (drain) current	$I_{pk} = \frac{5.5P_{out}}{V_{in}}$
Peak collector (drain) voltage	$V_{pk} = V_{out}(N_1/N_2) + V_{in}$
Approximate primary L	$L_{pri} = \frac{V_{in(min)}DC_{max}}{I_{pk}f}$

Figure 4.5

The flyback regulator.

flyback periods are rarely equal in time. One nice relationship is valid, though, when viewed from any one winding: the volt–time product of a winding during the power switch’s on-time is equal to the volt–time product during the flyback period (see Fig. 4.5).

The flyback regulator can operate in either the discontinuous or continuous mode. In the discontinuous mode, the energy stored in the core

**Figure 4.6**

(A) Flyback operating in the discontinuous mode; (B) flyback operating in the continuous mode.

from the power switch's conduction period is completely emptied from the core during the flyback period. The occurrence of this mode can be seen easily by viewing the power switch's voltage and determining whether the flyback voltage returns to the input voltage level prior to turning back on again. There may be some ringing during this time since both the power switch and the diode are turned off, leaving the transformer completely unloaded. In the continuous mode, the power

switch is turned on before the core empties itself of flyback energy (see Fig. 4.6). A typical flyback regulator may operate in either mode depending on the output load and the input voltage level. The flyback regulator will enter the continuous mode at low input line conditions when the increase in on-time pulsewidth does not allow enough time for the core to empty itself of the stored energy. For most flyback regulators, this also indicates that the regulator will soon be falling out of regulation. If the engineer designs the transformer for the heaviest expected load at the lowest expected input voltage, then everywhere else within the operating range the flyback regulator will simply shut down between cycles (discontinuous mode) and wait for the load demand to catch up with the power delivering capability. This capability allows the flyback supply to exhibit the broadest dynamic range (i.e., to regulate over a large range of input voltage and load current) of all the regulator topologies.

The operation of the flyback supply is a little more complicated to understand than that of the forward-mode regulators, but mathematically it is quite simple. Unlike a forward-mode transformer, the primary and secondary windings are wired out of phase so the primary and secondary currents do not flow simultaneously. Thus, the primary and secondary windings can be viewed as elementary inductors during their respective conduction periods. So, the input current can be described as follows:

$$i_{\text{pri}} = \int_{t=0}^{T_{\text{on}}} \frac{V_{\text{in}}}{L_{\text{pri}}} dt \quad V_{\text{in}} \text{ is a constant} \quad (4.2)$$

or

$$i_{\text{pri}} = \frac{V_{\text{in}}(T_{\text{on}})}{L_{\text{pri}}}$$

Similarly, the secondary current is

$$i_{\text{sec}} = \frac{V_{\text{out}}(T_{\text{fbk}})}{L_{\text{sec}}} \quad (4.3)$$

In the case of the secondary, the output inductance is a “charged” inductor discharging into a constant voltage load. Indeed, the output inductance may appear to be acting like a voltage source, but it is actually a current source being clamped by the voltage of the output capacitor. The energy entering the primary winding is given by

$$W = L \int_{t=0}^{T_{\text{on}}} (i_{\text{pk}} - i_{\text{min}}) dt \quad \text{or} \quad W = \frac{1}{2} L (i_{\text{pk}} - i_{\text{min}})^2 \quad (4.4)$$

This represents the energy entering the core during each cycle of the regulator. To compare this energy to the demands of the load, the designer multiplies W by the operating frequency of the supply. The result is then given in watts, which can be directly compared to the demand of the load, which is also measured in watts. One can see from these equations the overwhelming temptation facing the designer of the flyback supply—the designer can deliver more power to the load and shrink the transformer by decreasing the primary inductance and accepting a higher peak current. This trade-off works fine to a point. At the higher peak currents, the reliability of the semiconductors within the regulator are adversely affected. So don't get too carried away with minimizing the size of the transformer.

The flyback transformer, because of its unipolar use of the $B-H$ curve, does exhibit very high flux excursions that could easily result in the core material entering saturation. When this happens, the linear current ramp exhibited by the flyback during the power switch on-time quickly becomes nonlinear and proceeds rapidly toward infinite current. This happens because the permeability of the core material in the saturation region quickly drops, which causes the value of the inductance to disappear, hence resulting in only the power switch appearing across the input line. Obviously, the power switch was not designed to endure such conditions. A problem can arise when the regulator is in operation at the high input line voltage and an instantaneous increase in the demand of the load occurs which causes the error amplifier to demand the widest pulsewidth possible. If the deadtime has been set for low input line conditions, the core could enter saturation. Within microseconds the power switch could fail. To avoid situations like this, the designer should place an airgap within the core to discourage the core from entering saturation (see Chapter 6).

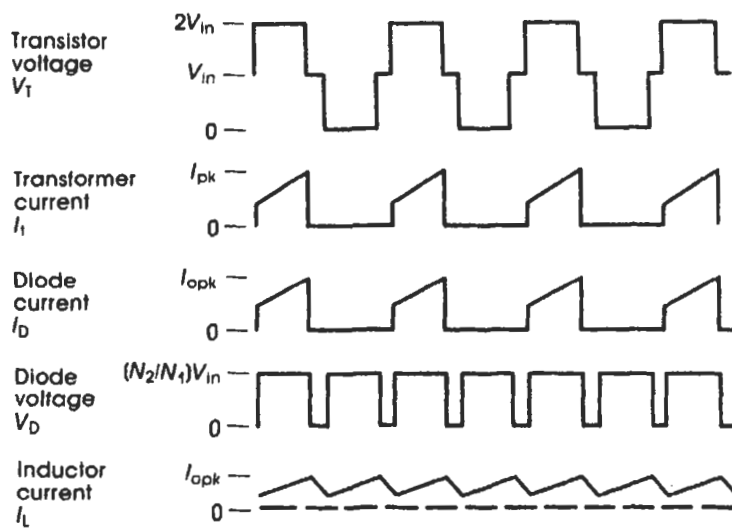
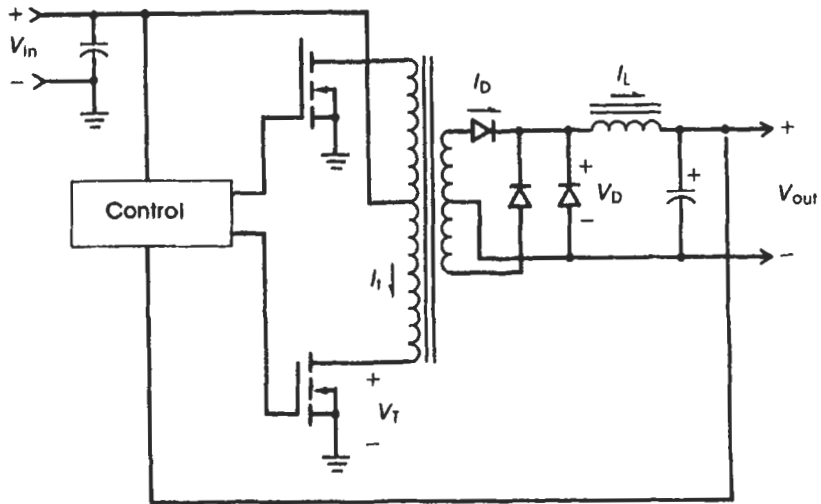
4.3.2 The Push–Pull Regulator Topology

The push–pull topology is a transformer-isolated forward-mode regulator. Because it is a forward-mode regulator, it has the “buck” style $L-C$ filter network on its output(s). The transformer is used, in this case, as a stepping-up or stepping-down function of the chopped input voltage waveform before it is presented to the output $L-C$ filter(s). Unlike the flyback transformer, the push–pull transformer does not store any energy and the output current is drawn when either power switch is conducting. The push–pull topology utilizes a center-tapped primary wind-

ing. The input line is connected to the center-tap and a power switch is connected to both ends of the winding. The secondary voltage is full-wave-rectified and then presented to the output L - C filter.

The push-pull regulator is what is called a *double-ended topology*, where two power switches share switching function. The power switches do not simultaneously conduct but alternate back and forth on alternate cycles. The two sides of the primary are wound in the same sense (or direction) but the current flows in the opposite direction. This results in the flux generated within the core material being driven in both the positive and negative flux polarities. This utilizes the core material in a more efficient manner, which can reduce the required core size. This can make the push-pull transformer core smaller than a comparable single-ended core if one neglects doubling of the windings on the transformer. The second advantage is that this topology can provide twice the output power of a single-ended topology operating at the same frequency. The two power switches share in the responsibility of eliminating the heat that is built up in them. This feature renders the push-pull topology capable of generating many hundreds of watts on its outputs.

The operation of the push-pull regulator is not difficult to understand (see Fig. 4.7). Only one transistor can turn on at any one time. When the transistor turns on, current begins to flow through its side of the primary. Simultaneously, one-half of the center-tapped secondary winding begins to conduct, thus forward-biasing its respective rectifier. This current then flows into the L - C filter and is, in turn, stored by the inductor and capacitor. The voltage that appears on the L - C filter has the peak value of the input voltage times the turns ratio from the primary to the secondary. This continues until the transistor is turned off by the controller. Next there must be a mandatory "deadtime" where neither transistor is conducting. This is because it takes a finite amount of time for the power switches to actually stop conducting current. In the case of bipolar power transistors, this could take as much as $2\ \mu\text{sec}$, depending on their drive circuits. For power MOSFETs, the time is much shorter, typically 50 to 400 nsec. It is critical that the power switches not conduct at the same time since this causes an effective short-circuited turn within the transformer, and astronomical levels of current could flow through the power switches, causing their immediate or latent destruction. When the opposing power switch turns on, a voltage equal to twice the input voltage appears across the inactive power switch. This is caused by current flowing in the opposite direction in the active half of the primary winding. Also during this period, the oppos-



Estimated parameter	Equation
Peak collector (drain) current	$I_{pk} = \frac{1.4P_{out}}{V_{in(min)}}$
Peak collector (drain) voltage	$V_{pk} = 2V_{in(max)}$

Figure 4.7
Push-pull regulator.

ing secondary rectifier conducts. So each power switch and rectifier operates at half the power supply operating frequency, but the switching characteristics must be as good as if they were operating at the full operating frequency.

The current waveform as viewed from the primary of the transformer is not really a function of the transformer but rather that of the output filter section magnetically reflected through the transformer. The transformer, though, must have sufficient inductance and core cross-sectional area as to not enter a saturated condition. At the point of transformer saturation, all ability to couple energy to the secondary disappears and the energy exits the transformer through the power switches, resulting in their destruction. The secondary of the transformer, resembles a voltage source like the power switch in the buck regulator. Once again, the current waveform flowing through the output filter inductor follows the buck regulator mathematical model:

$$I(\text{induct}) = I_{\min} + \frac{[(V_{\text{sec}} - V_{\text{rect}}) - V_{\text{out}}] T_{\text{on}}}{L}$$

(on)

$$I(\text{induct}) = I_{\text{pk}} - \frac{(V_{\text{out}} + V_{\text{rect}}) T_{\text{off}}}{L}$$

(off)

Like the buck regulator, the inductor must not become emptied of flux. Typically, the minimum current point is 50 percent of the rated load current. So the secondary current waveform is a current ramp sitting atop a pedestal of approximately one-half of the output current. This waveform is then multiplied by the inverse turns ratio of the transformer to obtain the waveform as seen from the primary.

Although this regulator topology can handle up to several kilowatts in output power, it suffers from one serious flaw. Its problem arises from certain definite real-world factors. Specifically, no two power switches are identical and no two halves of a center-tapped winding are identical. This means that one side of the primary will have a fraction of a turn less than the other side or that the power switch will turn off slightly slower or have a slightly lower saturation voltage. This condition guarantees that the transformer core will never operate symmetrically about the origin of the $B-H$ curve. This results in one side of the primary having a higher peak current and being nearer to saturation than the opposing side. This, in itself, is not a problem until a step increase output load current occurs. The error amplifier will drive the power