

# Switching regulators demystified

By Tom Mathews, principal engineer

You can see the proliferation of switching regulators throughout the electronics industry. These versatile devices can perform many functions, including voltage regulation, current regulation, or both. The fundamental theory behind the operation of the switching regulator is relatively simple. However, like any engineering endeavor, close attention to detail is important to avoid problems and poor performance. Key to good design of switching-regulator circuits is a solid understanding of the fundamental theory of operation.

## Background

Like their venerable cousin the linear regulator, switching regulators can reduce and regulate an input voltage. Switching circuits of this type are called buck regulators. Unlike their linear equivalent, switching regulators have a key advantage because that efficiency is far better. Switching-regulator efficiencies can be as high as 97%. High efficiencies are particularly of value in battery-operated circuits. Furthermore, the increased efficiency of a switcher usually leads to significant reductions in unwanted heat dissipation. Many switching-power designs can eliminate a heat sink that the equivalent linear design would otherwise require.

Another feature of the switching regulator is its ability to step up (increase) dc voltages. This type is the boost regulator. You may also know the boost regulator as a dc/dc converter. Boost regulators (and buck regulators, as well) perform a function that is very similar to that performed by a transformer, only at dc. In fact, the voltages and currents at the input and output of a switcher behave in a way that is almost identical to the behavior of a transformer.

Other variations on switching-supply design include isolated output converters and buck and boost conversion. Isolation eliminates any connections between the input ground and the output ground and allows the output voltage to “float.” An isolated design usually incorporates a transformer to provide the isolation for the switching currents and an optical isolator to isolate the feedback-sensing voltage.

The buck/boost switcher is a special hybrid of both the buck and boost functions. This type of switcher can shift gears from buck to boost when its input voltage falls below the output voltage. This type of design is of particular value in battery-operated systems in which the battery voltage is expected to fall below the required regulator output voltage. Because of this ability, the buck/boost can continue to provide regulation as battery voltages drop below the output and hence can more fully drain a battery, resulting in an apparent increase of battery life.

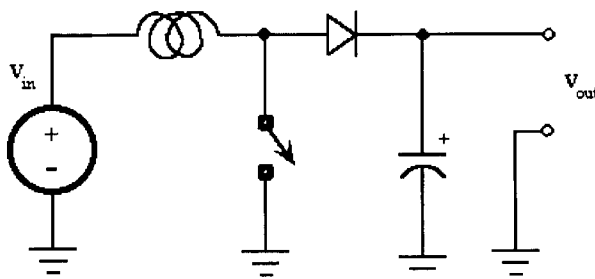


Figure 1 – Basic boost circuit

# Magnetics

The magnetics provide the heart of any switching supply. Switching regulators use both solenoid-wound inductors and toroidal inductors that are usually wound on high-permeability cores. You also see transformers, especially in isolated designs. Because of their key role, inductors and their behavior warrant a simple review. Much like a capacitor, an inductor stores energy. A capacitor stores its energy in an electric field, and the inductor stores its energy in a magnetic field. This field builds up as current flows through the inductor and, once established, resists change. The inductor equation states that the voltage at the inductor's terminals is proportional to the rate of change (slope) in current through the inductor ( $di/dt$ ). The constant of proportionality is the inductance ( $L$ ):

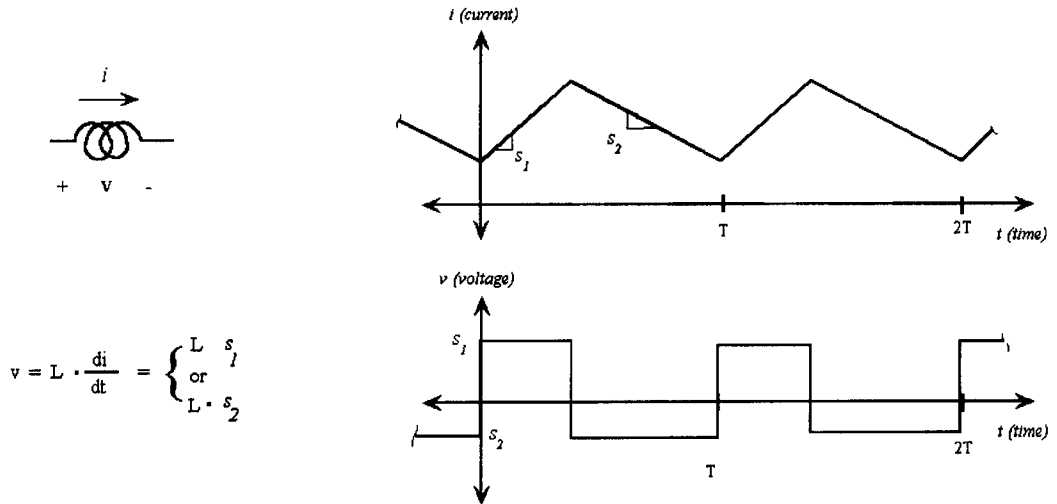


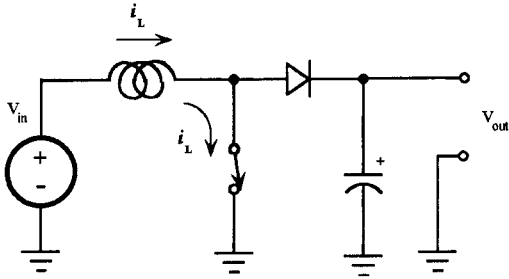
Figure 2 – Inductor behavior

Notice that if an instantaneous change in current were to occur, then an infinite voltage would result at the inductor terminals. Because nature dislikes infinite-voltage steps, the inductor does its best to resist any rapid changes in current. The switching-regulator design takes advantage of this fact. Controlled changes in inductor current create abrupt changes in voltage at the terminals of the inductor.

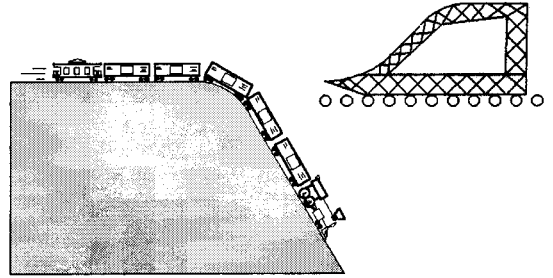
A mechanical analogy to this idea is momentum. The current through the inductor is much like a freight train; once the train is in motion, it wants to continue at its current speed and is difficult to stop. Similarly, the inductor does not allow abrupt changes in the current through its coils.

## Freight-train analogy—the boost circuit

A simplified diagram of a boost switching regulator appears below. The diagram examines two phases of operation. The first phase, phase I, is the build-up of current in the inductor. This build-up occurs when the switch is closed and continues for a predetermined amount of time. Similarly, an unpowered train resting on a flat surface builds up speed as its front half rolls down a hill.

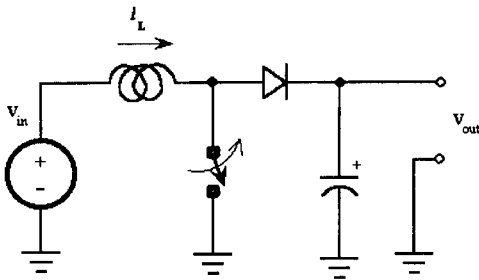


*Phase I – Build up of inductor current.*

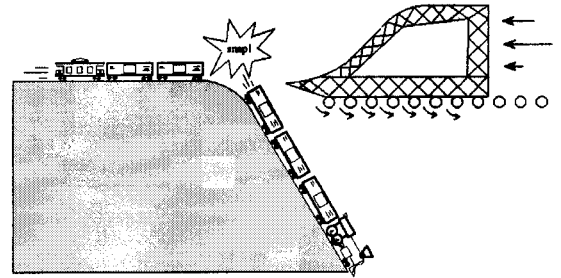


*The train builds up momentum.*

Once a current establishes in the inductor, the switch opens. Because the current through the inductor resists change, it must continue to flow. It has no choice but to flow through the diode and to the output. This change in current causes a step voltage to appear across the inductor. The current flows to a higher voltage at  $V_{out}$ .

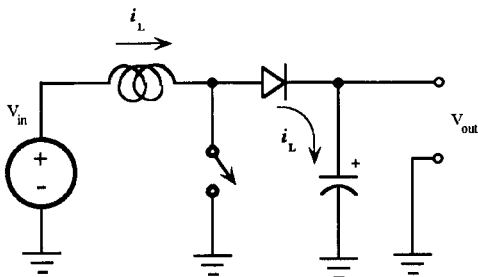


*Start of phase II - The switch opens*

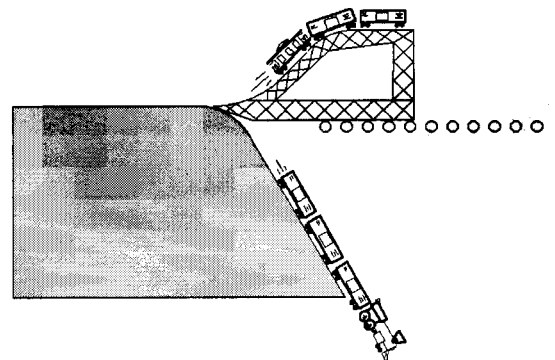


*The train breaks in two, and the bridge moves into place.*

Like the current in the inductor, the trailing cars of the freight train roll to a higher position (voltage) because of their momentum.



*Phase II – Inductor current flows into the load.*



*The trailing cars flow to a higher voltage.*

## Regulation by duty-cycle control

Figure 3 shows the inductor current for the two phases of the boost cycle. For most modern switching regulators, the frequency ( $f$ ) of the switching action is fixed. This frequency can be as high as several megahertz but usually ranges from 10 to 300 kHz. Higher frequency operation has the advantages of smaller and lower cost inductors. The duty cycle,  $\rho$ , is the ratio of the time spent in phase I to the total time in one switching cycle ( $T$ ). During steady-state operation, duty cycle is constant and varies only during changes in the load current. Because of this fact, the modern switching design has the advantage that spectral output (ac noise) is predictable and well-behaved.

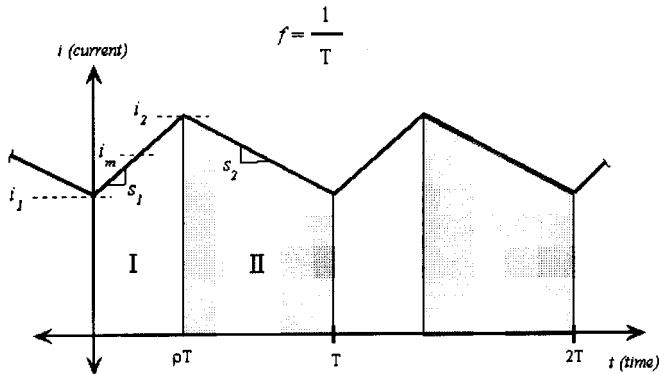


Figure 3 – Two phases of a boost cycle

The average input current to the circuit that Figure 3 represents is  $i_m$ . It is important to realize that the average output current is less and is  $i_m(1-\rho)$  because it arrives at the load only during phase II of the switching cycle. For the average load current to increase or decrease to maintain regulation, the average level of the sawtooth-current waveform in Figure 3 must be controlled. You achieve this control by temporarily increasing the duty cycle for an attack phase and by temporarily decreasing the duty cycle for a decay phase. Notice that these changes in duty cycle are only temporary and that the switching duty cycle returns to a steady-state operating point once you establish the new average current level. Figures 4 and 5 graphically show the attack and decay phases, respectively.

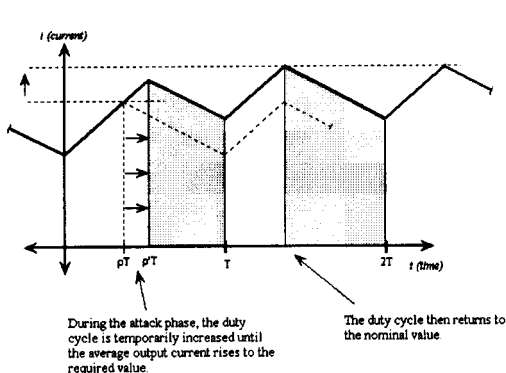


Figure 4 – The attack phase

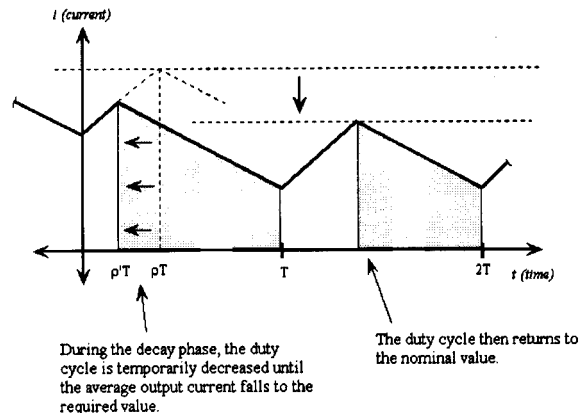


Figure 5 – The decay phase

# The buck circuit

The buck circuit is similar in operation (**Figure 6**); however, the arrangement of the components is different. The benefit of the buck circuit is its ability to step down a voltage while maintaining much higher efficiencies than are possible with traditional linear regulators. During phase I of the buck cycle, the switch is closed, and current flows through the inductor. When the switch opens, the inductor “insists” that current must continue to flow. Thus, current draws from ground through the diode. Because the source supplies current only for that period when the switch is closed, the input current is less than the output current. This situation is unlike that of a linear regulator, in which the input current is always equal to or greater than the output current.

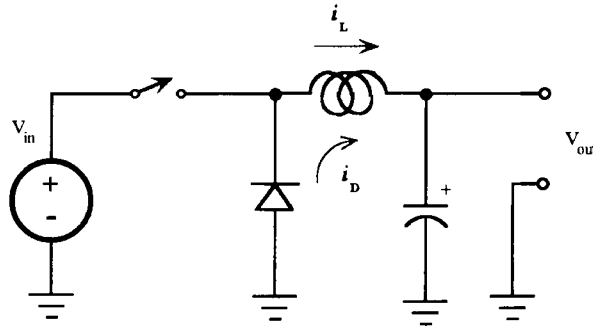


Figure 6 – Basic buck circuit

The current limit of the switching element primarily restricts the maximum limit for load current with the buck circuit. You achieve the maximum output current when the switch is on 100% of the time. Hence, a 1-to-1 relationship exists between switch ampacity and output current. This 1-to-1 relationship does not exist in most other switching topologies.

## Isolated designs

Power-supply design often requires an isolated output. Isolation exists when there is no physical dc electrical connection or dc path between the input and the output.

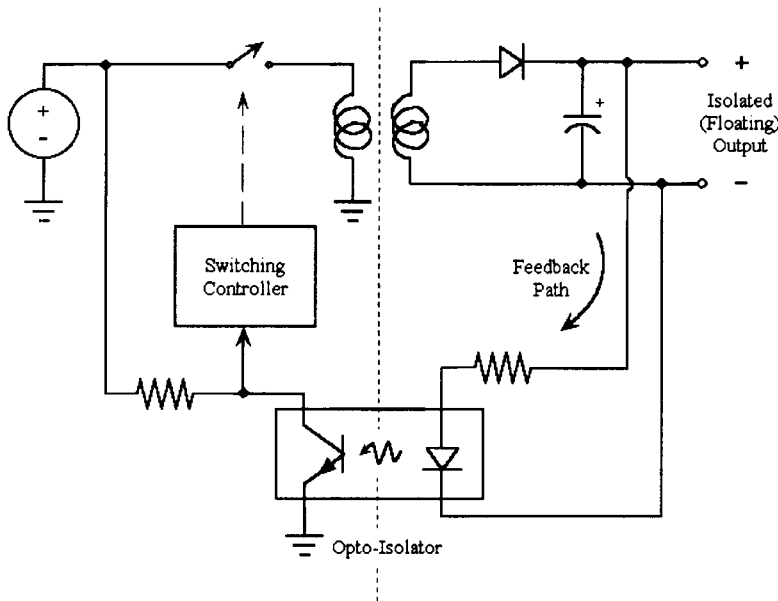
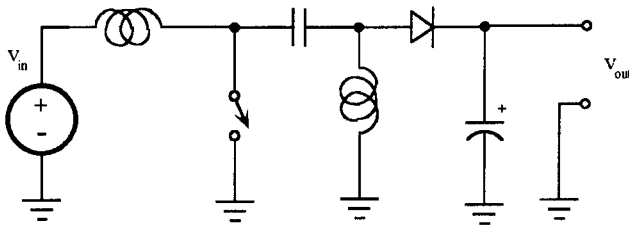


Figure 7 - Simplified isolated-switcher design

The most common way to achieve isolation is with transformers and optoisolators. You use the transformer to perform the isolated transfer of power to the load, and you use the optoisolator for the feedback signal. Safety reasons often dictate a need for isolated designs. If the primary-side voltages are derived from ac line, then the isolation provides electrical-shock protection for the secondary side. You can also ground an isolated output to any grounding system (within limits) without worry that ground-loop currents will flow. Note that by controlling the transformer turns ratio, the isolated topology can either buck or boost an input voltage. Also, because the output is isolated, you can obtain a negative output simply by grounding the positive output terminal. Because of these many advantages, the isolated design is very popular.

## SEPIC designs

The SEPIC (single-ended primary-inductance-converter) circuit shows up periodically. One key advantage of the SEPIC topology is that it is a buck/boost switcher. This type is particularly useful in battery circuits in which the battery voltage may drop below the output voltage as the battery discharges. The SEPIC topology extends battery life because the battery can more fully discharge. **Figure 8** is a simplified diagram of the SEPIC circuit.



*Figure 8 – Basic SEPIC topology*

Although the output is capacitively coupled to the input, the SEPIC topology in **Figure 8** is not isolated. This fact is because the ground of the switch must connect to the ground of the secondary-side inductor to balance the charge on the coupling capacitor. The main drawback of the SEPIC is the presence of large ac currents in the main coupling capacitor. This ac ripple current dictates the size of the coupling capacitor and often results in a need for a physically large and often impractical capacitor.

## The controller

To simplify the explanations, this article leaves out the details about how to control the switch for all of the aforementioned switching circuits. In real-world circuits, it is necessary to control the switching element and to do so in such a way that accommodates feedback for the purpose of voltage regulation.

Although several controller types exist for switching-power supplies, the voltage-mode SR (set/reset) flip-flop circuit is perhaps the simplest and most common. **Figure 9** illustrates this circuit. When the feedback voltage from the switching-circuit output is too low, the comparator output is high, and the clocking waveform passes through the AND gate. In this mode, the full duty cycle of the oscillator passes to the Q output of the SR flip-flop. When the feedback voltage is too high, the output of the comparator is low, and the AND gate inhibits and delays the setting action on the SR flip-flop. This situation extends the off time and reduces the duty cycle of the Q output. The circuit eventually reaches an equilibrium state, and maintaining steady-state regulation requires only small advances or retardations of the duty cycle. The attack and decay phases in **Figures 4** and **5** also show this action. Note that the frequency of the waveform at Q is constant as long as sufficient current draw exists. If the current draw drops to a very low level, this circuit goes into a “pulse-skipping” mode in which, for some cycles, no output pulse exists at all. A lower

switching frequency results because some pulses are totally removed from the otherwise constant frequency-switching waveform at Q.

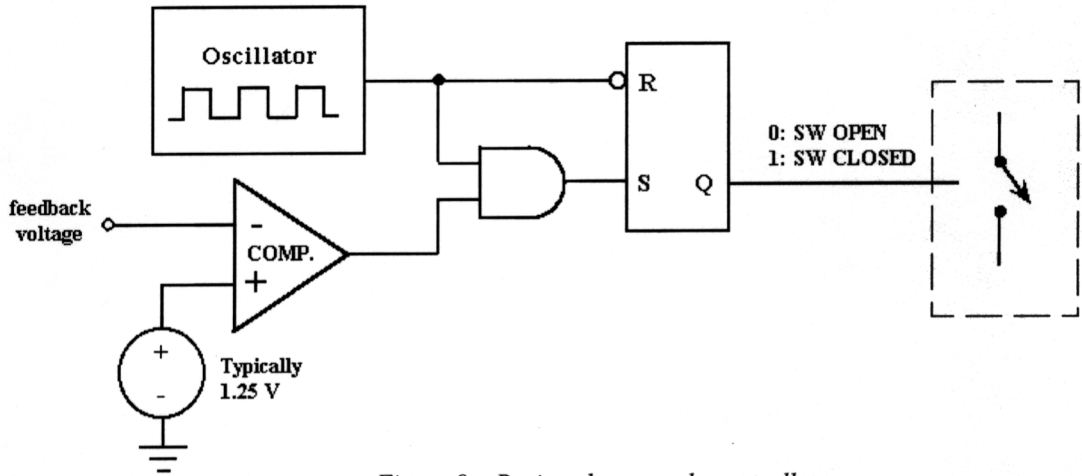


Figure 9 – Basic voltage-mode controller

## Losses and efficiency

The key benefits of switching regulation are the high efficiencies that are possible. Switching regulation steps up or steps down current without paying the  $V \cdot I$  penalty that you encounter with linear regulation. The FET switch, the inductor, and the catch diode, among other places, lose some power. The overall efficiency of the switching circuit is the ratio of power output to power input and is usually in the 70 to 95% range.

$$v_{out} \cdot i_{out} = \frac{\varepsilon}{100\%} \cdot v_{in} \cdot i_{in}$$

where  $\varepsilon$  = % efficiency

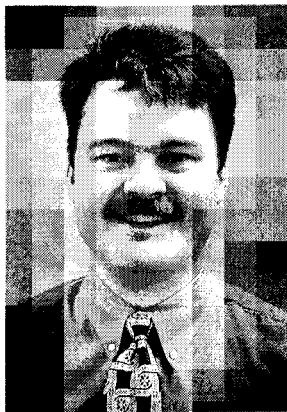
## Curious behavior at the input

An interesting phenomenon that occurs with switching regulators is the presence of negative dc resistance at the input to the switcher. This event happens because the input current to most switching circuits goes down when the input voltage increases! Because the effective negative resistance of the input is quite high, this behavior can create stability problems only if the switcher drives from a very high source impedance.

## Conclusion

Although mystifying at first glance, switching circuits are relatively straightforward. Once you understand the theory of the basic boost circuit, the operational theory of the more advanced topologies becomes clearer. The high efficiencies of switchers make them ideal for battery-operated applications. Switchers' ability to boost dc voltages and to provide isolation makes them a popular choice for a variety of other design applications as well.

## Author



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## References

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2. Gottlieb, Irving M, *Power Supplies, Switching Regulators, Inverters, and Converters*, TAB Books, a division of McGraw-Hill Inc, New York, NY, 1994.
3. Ambatipudi, Ravindra, *Design of Isolated Converters Using Simple Switchers*, National Semiconductor AN-1095, August 1998.



**D**C POWER supplies that use pass transistors or IC regulators must be capable of dissipating a great deal of heat. This can add to the cost of the supplies because of the need for large heat sinks and/or cooling fans. In addition, because the heat losses must be made up for by the power transformer, the transformer itself must have a fairly high current rating. This also adds to the expense. You can minimize the heat loss problem and reduce cost by using a switching regulator in your power supply designs.

The switching regulator acts as an ideal lossless switch. It applies power to the load only when necessary to prevent the load voltage from falling below some preset limit. Conventional power supplies use the pass transistors or IC's to absorb and dissipate the excess input

ation of the basic free-running switching regulator circuit shown in Fig. 1 is fairly simple. Transistor *Q1* serves as the saturated switch that connects the unregulated dc input voltage to the load through inductor *L1*. The switching causes the input end of *L1* to instantly assume the value of the input voltage, but the voltage at the output end of *L1* cannot change instantly because of the presence of *C1*. Therefore, current flows through *L1* to charge *C1* and to supply the load.

When the potential on *C1* builds up to slightly greater than the level of reference voltage  $V_R$ , the error amplifier shuts off *Q1*. The voltage at the input of *L1* now attempts to reverse polarity but is prevented from doing so by *D1*. How-

tude of the ripple is greatly affected by the type of capacitor used for *C1*.

As a result of the heavy current surges caused by the switching action of *Q1* in power supplies that deliver 1 or more amperes to the load, noise voltage spikes with frequency components in the multi-megahertz range can be generated by the regulator. With proper construction precautions, however, the amplitude of this noise can be held down to the levels of the switching frequency's ripple.

Regulator efficiencies of up to 85% or 90% can be realized with load regulation of 1% and line regulation of 0.2%. The switching frequency should be just

# SWITCHING REGULATORS REDUCE POWER SUPPLY COST

*How switching regulators can be used in power supplies to lower heat loss and, thereby, keep costs down.*

BY DON RAUDENBUSH

power when the load voltage rises above some preset limit.

Operating as a saturated transistor switch, the switching regulator dissipates only the power lost during each switching cycle, plus the loss due to the residual collector-to-emitter saturation voltage of the switching transistor in the on condition. Depending on the output power demands of the power supply, the low level of these losses eliminates the need for fans, minimizes the size of the heat sink required, and cuts down on the size as well as the weight of the power transformer.

**Basic Circuit Operation.** The oper-

ever, the energy stored in *L1* causes a decreasing current to continue to flow in *L1* through *D1* toward *C1* and the load.

When the current falls to the point where *C1* is no longer receiving current, the voltage across the capacitor and load begins to decrease. When it falls slightly below  $V_R$ , the error amplifier turns on *Q1* to repeat the cycle. Resistor *R2* feeds back a small portion of the input voltage when *Q1* is conducting to insure positive switching action by the error amplifier.

The output ripple voltage at the switching frequency, represented by the rising and falling voltage across *C1* and the load, is typically about 0.3% rms with the input and output voltages normally used in solid-state circuits. The ampli-

above the audible range to prevent the regulator from "singing" without introducing unnecessary inductor and capacitor losses.

**Circuit Description.** A more detailed circuit of the switching regulator is shown in Fig. 2. The error amplifier is a standard 723 regulator IC. It is convenient to use because it has an internal reference source and an output power stage. Its frequency response is more than adequate for the switching frequencies required.

The voltage divider made up of *R1* and *R2* is selected to produce a potential equal to the desired output voltage, keeping in mind the reference current source capabilities of the 723 of 15 mA and the reference potential of 7.15 V.

The basic equation for determining

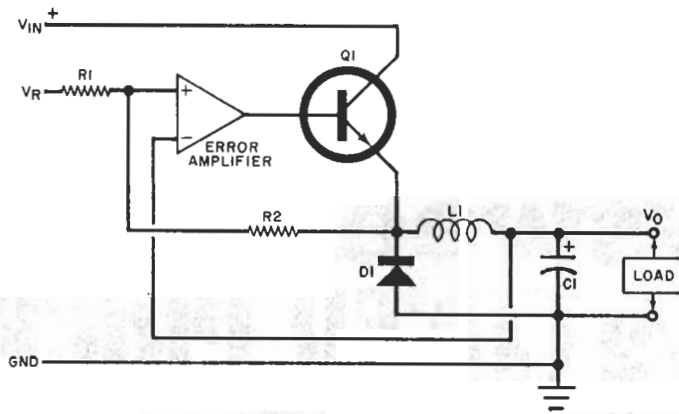


Fig. 1. Basic free-running switching regulator circuit. When output is too high, error amplifier cuts off Q1.

the values of  $C1$  and  $L1$  in the Fig. 2 circuit is

$$C1L1 = \frac{V_O(V_{IN} - V_O)}{8f^2V_{IN}(V_{OR} - V_{FB})} \times 10^9$$

Presented in this form, this equation emphasizes the relationship between  $C1$  and  $L1$  and the tradeoff possibilities of the values of these components. The value of  $L1$ , for example, can be decreased simply by increasing the value of  $C1$ .

In the above equation,  $L1$  is in millihenries,  $C1$  is in microfarads,  $f$  is in hertz, and all potentials are in volts. The unregulated dc input voltage to the regulator is represented by  $V_{IN}$ , while  $V_O$  is the regulated output voltage. For best operation,  $V_{IN}$  should be three to five times  $V_O$ . The  $f$  in the equation is the switching frequency, which should be about 20,000 Hz. The tolerable peak-to-peak output ripple voltage, usually between 50 and 75 mV, is represented by  $V_{OR}$ , while  $V_{FB}$  is the fraction of the input voltage (neglecting the  $V_{CE SAT}$  of switching transistor  $Q1$ ) this is fed back to the error amplifier. With  $R4$  much greater in value than  $R3$ ,  $V_{FB} = (V_{IN} R3)/R4$ . Resistor  $R3$ 's value should be about 1000 ohms so that with  $R4$ 's value set at 1 megohm,  $V_{FB}$  is kept small with respect to  $V_{OR}$ .

With a value on the order of 51 ohms,  $R5$  limits the base drive current to  $Q2$  through  $IC1$ . In the event of a short circuit at the output of the regulator,  $R5$  also prevents damage to  $IC1$ ,  $Q1$ , and  $Q2$ . Resistors  $R6$  and  $R7$  are included in the circuit to insure fast turn-off of  $Q1$  and  $Q2$ . The value of  $R6$  should be about 100 ohms, while the value of  $R7$  should be several thousand ohms. Capacitor  $C3$  provides a bypass to ground for voltage divider  $R3$ - $R4$ .

As an exercise in using the equation, let us determine the value of  $L1$  that will

be required for a regulator whose output is 5 volts at 2 amperes. Assume that the unregulated  $V_{IN}$  is 24 volts, that at this voltage the average current capability is 0.5 ampere, and that an output ripple voltage,  $V_{OR}$ , of 50 mV peak-to-peak can be tolerated.

Assuming switching frequency  $f$  is to be 20,000 Hz, we have all the information needed in the basic equation except the feedback voltage, which can be calculated as follows:  $V_{FB} = (24 \times 1000)/10^6 = 0.024$  volts, or 24 mV. Now let us also assume that the value of  $C1$  is 250  $\mu$ F. Plugging these values into the basic equation, we calculate the value of  $L1$  to be 0.19 mH.

The Magnetics Components Division of Spang Industries, Inc., Butler, PA 16001, offers a line of molypermalloy powder cores for winding inductors and an excellent catalog and applications

manual (No. MPP-303S). Using the Core Selector Chart in the manual, we would choose a core with a 1.06" (26.92-mm) outer diameter, 0.58" (14.73-mm) inner diameter, and permeability of 125. Calculations detailed in the manual indicate that 37 turns of 18-gauge wire will have to be wound on this core to handle the 2-ampere output current from the regulator.

It is interesting to compare the performance of the switching regulator to a conventional regulator that uses pass transistors to produce a 5-volt, 2-ampere output when the unregulated source is 24 volts. The pass transistor must drop the potential from 24 to 5 volts at 2 amperes, generating a heat loss of an equivalent 38 watts. The switching regulator, on the other hand, accomplishes the same thing with a heat loss of only 2 watts.

**Selecting Components.** When the output current of the regulator circuit is to be 1 or more amperes, the size of the wire used for the windings of  $L1$  must be quite large, as illustrated in the above example. Therefore,  $L1$  should have as small an inductance value as possible to save size, weight, cost, and winding time. If you do not wish to wind your own inductors, you can use an appropriate ET Series high-current inductor suitable for operation at switching frequencies made by Triad-Utrad Division of Litton Industries, 305 N. Briant St., Huntington, IN 46750.

The selection of output capacitor  $C1$  is extremely important in minimizing the output ripple. Usually an aluminum elec-

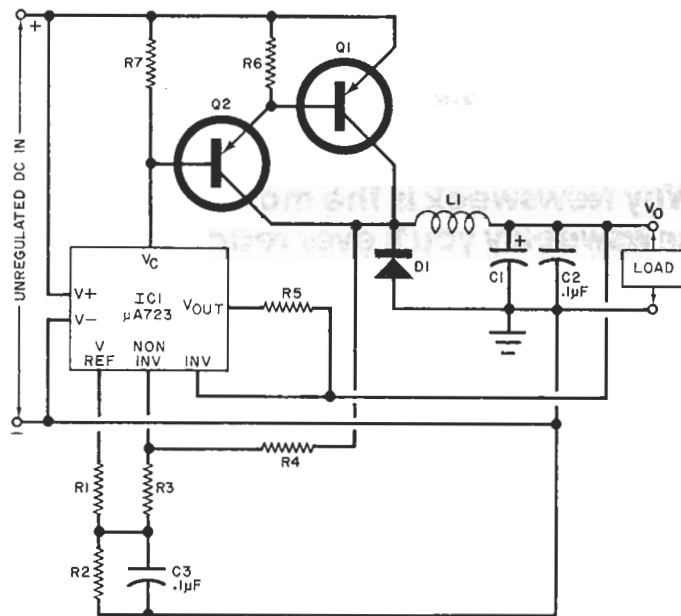


Fig. 2. Schematic diagram for a more sophisticated switching regulator using a 723 IC as the error amplifier.

trolytic this capacitor must have low stray inductance for optimum performance. Good results have been obtained using the Type BR "Blue Beaver" electrolytic capacitors made by Cornell-Dubilier. The company also offers a line of four-terminal electrolytics made specifically for switching regulator applications. Sprague Electric offers a similar line of capacitors.

Capacitor *C2* helps to minimize ripple and noise in the output voltage. Use a ceramic disc capacitor here.

For best efficiency, *D1* should be a fast switching silicon power diode with a rating in excess of the expected maximum load current. Not all silicon diodes fill the bill in this application. A line of diodes for use in switching regulators is made by Semtech Corp., 625 Mitchell Rd., Newbury Park, CA 91320.

Transistor *Q1* conducts the load current as pulses of a peak value equal to the output current. The losses that occur during switching because of the finite time taken by *Q1* to go from full cutoff to full saturation and vice-versa contribute significantly to the total power loss and cause the transistor to heat up. For this reason, *Q1* must be a fast silicon power switching transistor with an  $f_T$  of at least 4 MHz. Similarly, *Q2* should have a 4-MHz or greater  $f_T$ , but since it only drives the base of *Q1*, its current rating need be only 10% of that of *Q1*.

**Proper Construction.** In all but low-power supplies, *Q1* should be mounted with mica insulators on the metal chassis of the supply or to the chassis via a heat sink assembly.

The ground system of the power supply is perhaps the most important construction detail involved in minimizing switching noise. Ideally, a single-point ground system should be used, and particular attention should be given to using short leads to connect the unregulated input supply to the input of the voltage regulator circuit and the single-point ground. The chassis of the power supply should be connected to the regulator at only this point. The network made up of *C1*, *C2*, *D1*, and *L1* should be connected as physically close together as possible. The amount of care taken in building a power supply with a switching regulator will pay off in better operation and the less likelihood to generate noise. ◇

**Note:** Diagrams courtesy Fairchild Semiconductor Components group, which assumes no responsibility for circuits described other than entirely embodied in a Fairchild product. No other circuit patent licenses are implied.