Keywords: SMPS, power supplies, buck, boost, step-down, step-up, linear regulator

APPLICATION NOTE 4087

An Introduction to Switch-Mode Power Supplies

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Abstract: Switch-mode power supplies are a popular and sometimes necessary choice for DC-DC power conversion. These circuits offer distinct benefits and tradeoffs when compared to alternative methods of converting DC power. This article presents a brief summary of the advantages and tradeoffs of switch-mode power supplies, and also offers a simple review of their operation and theory.

This article was also featured in Maxim's Engineering Journal, vol. 61 (PDF, 440kB).

Considering the multiple DC voltage levels required by many electronic devices, designers need a way to convert standard power-source potentials into the voltages dictated by the load. Voltage conversion must be a versatile, efficient, reliable process. Switch-mode power supplies (SMPSs) are frequently used to provide the various levels of DC output power needed for modern applications, and are indispensable in achieving highly efficient, reliable DC-DC power-conversion systems.

Why SMPS?

The majority of electronic DC loads are supplied from standard power sources. Unfortunately, standard source voltages may not match the levels required by microprocessors, motors, LEDs, or other loads, especially when the source voltage is not regulated. Battery-powered devices are prime examples of the problem: the typical voltage of a standard Li+ cell or NiMH stack is either too high/low or drops too far during discharge to be used in conventional applications.

Versatility

Fortunately, the versatility of SMPSs solves the problem of converting a standard source voltage into a usable, specified output voltage. There are numerous SMPS topologies, which are classified into fundamental categories—these power supplies step up, step down, invert, or even step up and down the input voltage. Unlike linear regulators, which can only step down an input, SMPS are attractive because a topology can be selected to fit nearly any output voltage.

Customization

Additionally, modern SMPS ICs are designed with varying levels of integration, allowing the engineer to choose among topologies with more or less of the standard SMPS features brought into the IC. In doing so, manufacturers ease the design burden for commonly used, application-specific power supplies or offer the engineer basic SMPS ICs for custom projects, thereby enhancing the versatility of these widely used devices.

Efficiency

Engineers also face the other common problem of how to convert DC power efficiently. For instance, it is often required to step down an input voltage to achieve a lower output voltage. A simple solution implements a linear regulator, as this device requires only a few capacitors and adequate thermal management. However,

where such simplicity ends, inefficiency begins—even to unacceptable levels if the voltage differential is large.

The efficiency of a linear regulator is directly related to the power dropped across its pass transistor. This power drop can be significant because dissipated power is equal to $I_{LDO} \times (V_{IN} - V_{OUT})$. For example, when stepping down a 100mA load from a 3.6V battery to a 1.8V output, 0.18W is dropped across the linear regulator. This power drop yields a low 50% efficiency, which reduces battery longevity by 50% (assuming ideal operation).

Understanding this efficiency loss, the dutiful engineer is driven to achieve an improved solution, and here is where the SMPS excels. A well-designed SMPS can achieve 90% efficiency or more, depending on load and voltage levels. As in the previous example, using the step-down SMPS of **Figure 1** instead of a linear regulator, 90% efficiency is observed. This is an efficiency improvement of 40% over the linear regulator. The advantage of the step-down SMPS is apparent, and similar or better efficiencies are observed in other SMPS topologies.
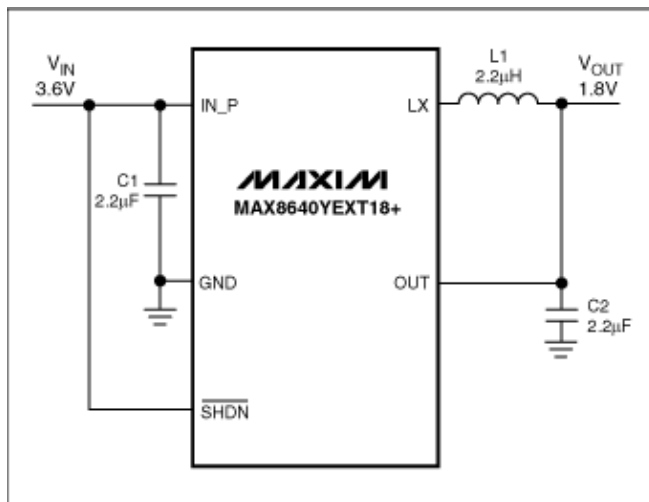

Figure 1. The MAX8640Y is used within a simple, step-down SMPS circuit.

Although high efficiency is the principal advantage with SMPS designs, other benefits naturally occur as a direct result of minimizing power loss. For example, a reduced thermal footprint is observed in the SMPS when compared to its less efficient counterparts. This benefit equates to reduced thermal-management requirements. Also, more importantly, lifetime increases due to improved reliability, because components are not subjected to excessive heat, as they would be in a less efficient system.

SMPS Topologies and Conversion Theory

As mentioned in the previous section, SMPSs can convert a DC input voltage into a different DC output voltage, depending on the circuit topology. While there are numerous SMPS topologies used in the engineering world, three are fundamental and seen most often. These topologies (seen in **Figure 2**) are classified according to their conversion function: step-down (buck), step-up (boost), and step-up/down (buck-boost or inverter). The inductor charge/discharge paths included in the Figure 2 diagrams are discussed in the following paragraphs.
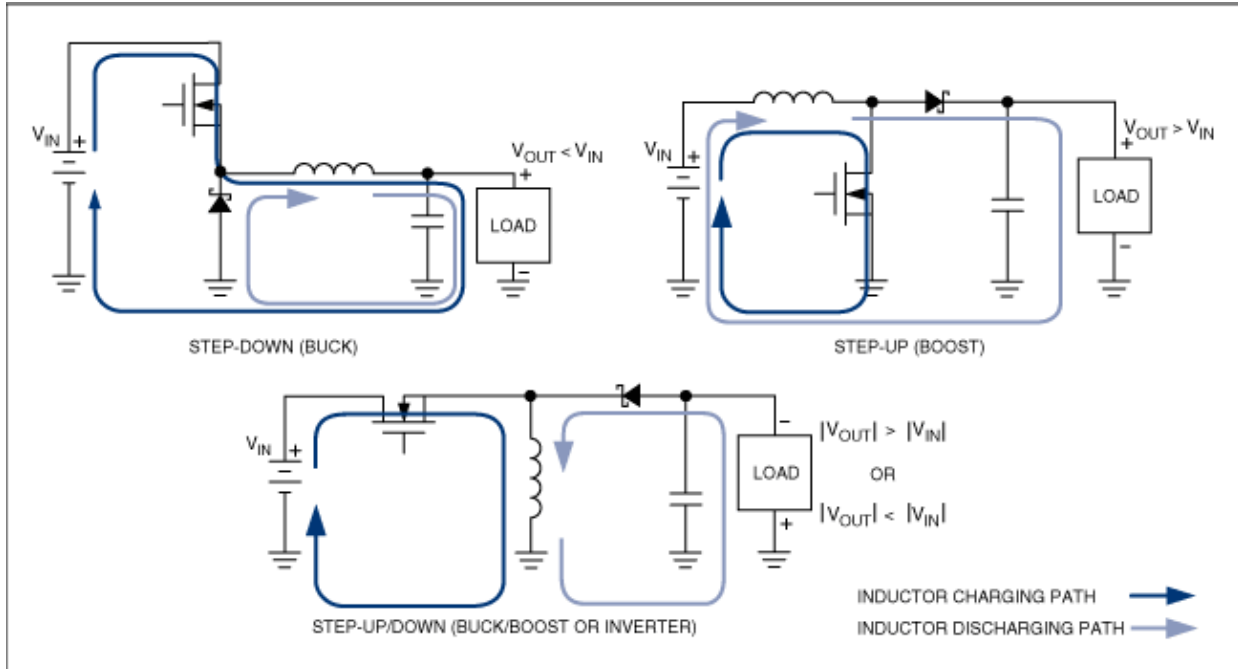
Figure 2. Buck, boost, and buck-boost compose the fundamental SMPS topologies.

All three fundamental topologies include a MOSFET switch, a diode, an output capacitor, and an inductor. The MOSFET, which is the actively controlled component in the circuit, is interfaced to a controller (not shown). This controller applies a pulse-width-modulated (PWM) square-wave signal to the MOSFET's gate, thereby switching the device on and off. To maintain a constant output voltage, the controller senses the SMPS output voltage and varies the duty cycle (D) of the square-wave signal, dictating how long the MOSFET is on during each switching period (T_S). The value of D, which is the ratio of the square wave's on time to its switching period (T_{ON}/T_S), directly affects the voltage observed at the SMPS output. This relationship is illustrated in equations 4 and 5.

The on and off states of the MOSFET divide the SMPS circuit into two phases: a charge phase and a discharge phase, both of which describe the energy transfer of the inductor (see the path loops in Figure 2). Energy stored in the inductor during the charging phase is transferred to the output load and capacitor during the discharge phase. The capacitor supports the load while the inductor is charging and sustains the output voltage. This cyclical transfer of energy between the circuit elements maintains the output voltage at the proper value, in accordance with its topology.

The inductor is central to the energy transfer from source to load during each switching cycle. Without it, the SMPS would not function when the MOSFET is switched. The energy (E) stored in an inductor (L) is dependent upon its current (I):

$$E = \frac{1}{2} \times L \times I^2 \qquad\qquad\qquad \text{Eq. 1}$$

Therefore, energy change in the inductor is gauged by the change in its current (ΔI_L), which is due to the voltage applied across it (V_L) over a specific time period (ΔT):

$$\Delta I_L = \frac{V_L \times \Delta T}{L} \qquad\qquad\qquad \text{Eq. 2}$$

The (ΔI_L) is a linear ramp, as a constant voltage is applied across the inductor during each switching phase (**Figure 3**). The inductor voltage during the switching phase can be determined by performing a Kirchoff's

voltage loop, paying careful attention to polarities and V_{IN}/V_{OUT} relationships. For example, inductor voltage for the step-up converter during the discharge phase is -(V_{OUT} - V_{IN}). Because V_{OUT} > V_{IN}, the inductor voltage is negative.
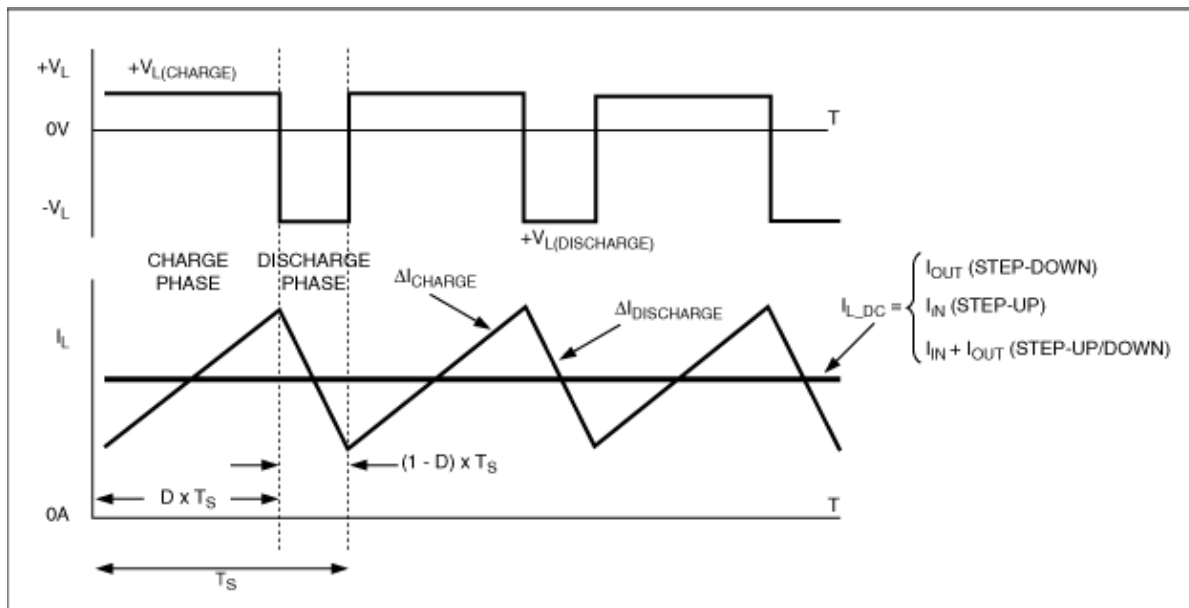

Figure 3. Voltage and current characteristics are detailed for a steady-state inductor.

During the charge phase, the MOSFET is on, the diode is reverse biased, and energy is transferred from the voltage source to the inductor (Figure 2). Inductor current ramps up because V_L is positive. Also, the output capacitance transfers the energy it stored from the previous cycle to the load in order to maintain a constant output voltage. During the discharge phase, the MOSFET turns off, and the diode becomes forward biased and, therefore, conducts. Because the source is no longer charging the inductor, the inductor's terminals swap polarity as it discharges energy to the load and replenishes the output capacitor (Figure 2). The inductor current ramps down as it imparts energy, according to the same transfer relationship given previously.

The charge/discharge cycles repeat and maintain a steady-state switching condition. During the circuit's progression to a steady state, inductor current builds up to its final level, which is a superposition of DC current and the ramped AC current (or inductor ripple current) developed during the two circuit phases (Figure 3). The DC current level is related to output current, but depends on the position of the inductor in the SMPS circuit.

The ripple current must be filtered out by the SMPS in order to deliver true DC current to the output. This filtering action is accomplished by the output capacitor, which offers little opposition to the high-frequency AC current. The unwanted output-ripple current passes through the output capacitor, and maintains the capacitor's charge as the current passes to ground. Thus, the output capacitor also stabilizes the output voltage. In nonideal applications, however, equivalent series resistance (ESR) of the output capacitor causes output-voltage ripple proportional to the ripple current that flows through it.

So, in summary, energy is shuttled between the source, the inductor, and the output capacitor to maintain a constant output voltage and to supply the load. But, how does the SMPS's energy transfer determine its output voltage-conversion ratio? This ratio is easily calculated when steady state is understood as it applies to periodic waveforms.

To be in a steady state, a variable that repeats with period T_S must be equal at the beginning and end of each period. Because inductor current is periodic due to the charge and discharge phases described previously, the inductor current at the beginning of the PWM period must equal inductor current at the end.

This means that the change in inductor current during the charge phase (ΔI_{CHARGE}) must equal the change in inductor current during the discharge phase ($\Delta I_{DISCHARGE}$). Equating the change in inductor current for the charge and discharge phases, an interesting result is achieved, which is also referred to as the volt-second rule:

$$\left| \Delta I_{CHARGE} \right| = \left| \Delta I_{DISCHARGE} \right|$$

$$\left| \frac{V_{L(CHARGE)} \times D \times T_S}{L} \right| = \left| \frac{V_{L(DISCHARGE)} \times (1 - D) \times T_S}{L} \right| \qquad \text{Eq. 3}$$

$$\left| V_{L(CHARGE)} \right| \times D \times T_S = \left| V_{L(DISCHARGE)} \right| \times (1 - D) \times T_S$$

Simply put, the inductor voltage-time product during each circuit phase is equal. This means that, by observing the SMPS circuits of Figure 2, the ideal steady-state voltage-/current-conversion ratios can be found with little effort. For the step-down circuit, a Kirchhoff's voltage loop around the charge phase circuit reveals that inductor voltage is the difference between V_{IN} and V_{OUT}. Likewise, inductor voltage during the discharge phase circuit is $-V_{OUT}$. Using the volt-second rule from equation 3, the following voltage-conversion ratio is determined:

$$\left| V_{IN} - V_{OUT} \right| \times D = \left| -V_{OUT} \right| \times (1 - D)$$

$$\frac{V_{OUT}}{V_{IN}} = D \qquad \text{Eq. 4}$$

Further, input power (P_{IN}) equals output power (P_{OUT}) in an ideal circuit. Thus, the current-conversion ratio is found:

$$P_{IN} = P_{OUT}$$

$$I_{IN} \times V_{IN} = I_{OUT} \times V_{OUT} \qquad \text{Eq. 5}$$

$$\frac{I_{IN}}{I_{OUT}} = \frac{V_{OUT}}{V_{IN}} = D$$

From these results, it is seen that the step-down converter reduces V_{IN} by a factor of D, while input current is a D-multiple of load current. **Table 1** lists the conversion ratios for the topologies depicted in Figure 2. Generally, all SMPS conversion ratios can be found with the method used to solve equations 3 and 5, though complex topologies can be more difficult to analyze.

Table 1. SMPS Conversion Ratios

Topology	Voltage-Conversion Ratio	Current-Conversion Ratio
Step-down	$V_{OUT}/V_{IN} = D$	$I_{IN}/I_{OUT} = D$
Step-up	$V_{OUT}/V_{IN} = 1/(1 - D)$	$I_{IN}/I_{OUT} = 1/(1 - D)$
Step-up/down	$V_{OUT}/V_{IN} = D/(1 - D)$	$I_{IN}/I_{OUT} = D/(1 - D)$

Disadvantages and Tradeoffs of SMPSs

Of course, the high efficiency afforded by SMPSs is not without its penalties. Perhaps the most often cited issue regarding switch-mode converters is their propensity to radiate electromagnetic interference (EMI) and conduct noise. Electromagnetic radiation is caused by the fast transitions of current- and voltage-switching waveforms that exist in SMPS circuits. Rapidly changing voltages at the inductor node cause radiated electric fields, while fast-switching currents of the charge/discharge loops produce magnetic fields. Conducted noise, however, is propagated to input and output circuits when SMPS input/output capacitances and PCB parasitics present higher impedances to switching currents. Fortunately, good component placement and PCB layout techniques can successfully combat EMI and reduce noise.

SMPSs also can be quite complex and require additional external components, both of which can equate to an increase in overall cost of the power supply. Fortunately, most SMPS IC manufacturers provide detailed literature not only about device operation, but also about choosing correct external components. Additionally, the high levels of integration in modern SMPS ICs can reduce the number of external components required.

Despite these issues, SMPSs are widely used in numerous applications. The disadvantages can be managed, and the efficiency and versatility gained from their use is very desirable, and often required.

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