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Keywords: regulator, power supply, regulator topologies, switching regulator, step-up, step-down, inverter, linear regulator, charge pump, buck, boost, flyback

TUTORIAL 660

Regulator Topologies for Battery-Powered Systems

Jan 31, 2001

Abstract: This tutorial presents an overview of regulator topologies for battery-powered equipment. The discussion covers linear regulators, charge pumps, buck and boost regulators, inverters, and flyback designs. The importance of peak current is explained, and schematics of each topology are shown.

A similar version of this article appeared in the January 20, 1994 issue of *EDN*.

Introduction

Power supplies are perhaps the most crucial elements of a battery-powered system. Knowledge of some basic regulator topologies will help you select and design the right supply configurations for your needs. This tutorial presents an overview of regulator topologies for battery-powered equipment. The discussion covers linear regulators, charge pumps, buck and boost regulators, inverters, and flyback designs. The importance of peak current is explained, and schematics of each topology are shown.

Regulator Topology Overview

Desktop computers, laptops, netbooks, smartphones, PDAs, and many other consumer electronic devices usually require more than one power supply. These devices may need an AC/DC adapter, a battery charger, a high-voltage DC/AC converter for the backlight, and other supplies for lasers, cellular radio transmitters, and auxiliaries. **Table 1** shows the seven most common regulator topologies beginning with the simplest (the linear regulator) and progressing to more specialized types (like the flyback regulator). The table also lists the pros and cons of each topology.

Swapping components in a basic switching-regulator layout alters the circuit topology to create regulators that step up (boost), step down (buck), or invert an input voltage. Substituting a transformer for the inductor produces at least two more regulator circuits or auxiliary output voltages.

Table 1. DC/DC Topology Hierarchy

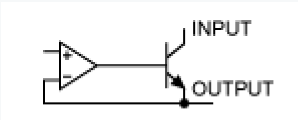
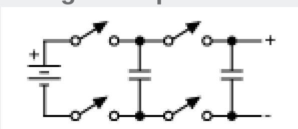
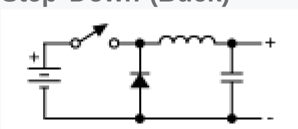
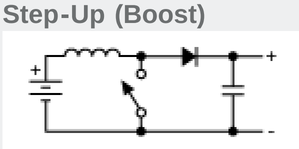
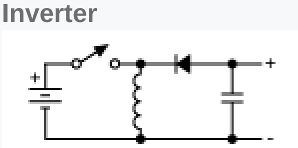
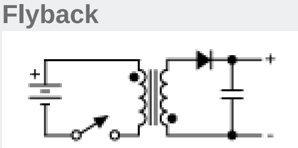
	Pros	Cons
Linear Regulator 	• Inexpensive • Very small • Low quiescent current (I_Q) • Low-noise/EMI	• V_{OUT} must be less than V_{IN} • Inefficient at high-input voltages and/or large loads
Charge Pump 	• Inexpensive • Very small • Can boost or invert	• Limited output power • Limited range of input/output voltage ratio
Step-Down (Buck) 	• Lowest peak current of any switching-regulator configuration • Only one switch voltage drop • Low-ripple current in output-filter capacitor • Simple inductor • Low switch-stress voltage	• V_{OUT} must be less than V_{IN} • High-side switch
Step-Up (Boost) 	• Low peak current • Low-side switch • Simple inductor • Low switch-stress voltage	• V_{OUT} must be greater than V_{IN} • Output cannot be completely turned off • No short-circuit protection
Inverter 	• Simple inductor	• Negative output only • High-side switch • High peak currents
Flyback 	• Isolated output • Multiple outputs • Steps up/down, inverts • Low-side switch	• Transformer instead of inductor • High peak currents • High switch-stress voltage

Table 1 omits complex topologies like resonant-mode regulators, because their control circuitry consumes too much power for small battery-operated systems. The rule for these systems is simplicity: the simpler the circuit, the better. Simple circuits have no magnetics, simple inductors, or 1:1 transformers. Off-the-shelf magnetics simplify assembly and minimize costs. Other topologies can be derived from the basic topologies in Table 1. This includes the Cuk converter, which combines the buck and boost topologies, and the forward converter, which combines a buck converter with half of a push-pull converter. However, these topologies are not discussed in detail in this tutorial.

Linear Regulators

Linear regulators are the simplest and least expensive of the power-supply circuits, but this ease of use generally comes at a cost. As indicated in Table 1, a linear regulator includes a feedback network that monitors the output voltage and adjusts it by controlling an internal pass transistor (BJT or FET). When the input voltage greatly exceeds the output voltage, this pass transistor dissipates large amounts of energy (in the form of heat) at high loads. This results in lower efficiency than a comparable switching regulator.

Linear regulators are especially useful in generating multiple voltages, when used in conjunction with a switching regulator. A switching regulator can boost a low battery voltage. However, rather than incorporate multiple switchers on a small board, the designer may use linear regulators for their low dropout voltages to generate voltage for downstream circuitry.

When using linear regulators in battery-powered systems, it is important to consider the quiescent current (typical and at full load), dropout voltage, thermal characteristics, and shutdown capabilities. **Table 2** shows a brief comparison of some available Maxim regulators.

Table 2. Linear Regulator Comparison

Part	Input Voltage Range (V)	Quiescent Current		Dropout Voltage (At 500mA Load) (mV)	Shutdown Current (µA)	Package
		No Load	I_{LOAD} = 500mA (µA)			
MAX15029	1.425 to 3.6	275µA	315	40	5.5	TDFN
MAX1806	2.25 to 5.5	210µA	575	201	0.02	µMAX®
MAX1589	1.62 to 3.6	70µA	90	175	0.01	TSOT, TDFN
MAX1935	2.25 to 5.5	210µA	575	201	0.02	TQFN

See Maxim's application note 751, "Linear Regulators in Portable Applications," for a detailed discussion about using linear regulators in battery-powered circuits.

Charge Pumps

Charge pumps use capacitors, instead of an inductor-switcher circuit, to generate an output voltage that is higher or lower than the input voltage. Regulated charge pumps can also invert the input voltage.

Generally, the load current that can be drawn from a charge pump is limited to a few tens of milliamps. The output voltage of an unregulated charge pump is dependent on the input voltage and drops proportionally as the output load increases. Regulated charge pumps are not dependent on the input voltage to set the output voltage and, because they are regulated, the output voltage remains constant over the entire load range. Some charge pumps are capable of handling up to 125mA (like the MAX1595) and a few are capable of driving loads up to 250mA (MAX682).

Charge pumps create noise as they charge and discharge the capacitor(s) connected to the device. Due to the light load limits and lack of an inductor, this noise is generally smaller in magnitude than a comparable switching regulator.

Switching Regulators

Switch-mode regulators are more efficient and versatile than their linear counterparts; however, they are also noticeably more complex. The parameters affecting the choice of a switching-regulator topology include the peak currents for the load and inductor, the voltage level on the power transistors, and the necessity for magnetic and capacitive energy storage.

Switch-mode regulators have two fundamental modes of operation: discontinuous conduction and continuous conduction. Discontinuous conduction allows the inductor current to decay to zero during each off period, which causes the stored energy to be transferred to the output filter during each switching cycle. In continuous-conduction mode, the inductor current includes a DC component proportional to the load. Operating in continuous-conduction mode lowers the ratio of peak inductor current to DC-load current. This, in turn, lowers the peak-to-peak ripple current and reduces the core loss.

Peak Current Is Critical

In battery-powered converters, the peak inductor current is important because it directly affects battery life and parasitic losses. It partly depends on the average load current, which varies with the regulator topology, the control circuitry, and whether the inductor current is continuous. Some sample equations for the peak inductor current for the step-up, step-down, and inverter regulators are shown in **Table 3**.

Table 3. Sample Peak-Inductor-Current Equations

Configuration	Device	Peak Inductor Current (A)
Step-Down/Buck	MAX8566	$I_{PEAK} = \left(1 + \frac{LIR^{*}}{2}\right) \times I_{OUT(MAX)}$
Step-Up/Boost	MAX15059	$I_{PEAK} = \sqrt{\frac{2 \times T_S^{**} \times (V_{OUT} - V_{IN}) \times I_{OUT(MAX)}}{\text{ç} \times L}}$
Inverter	MAX1846	$I_{PEAK} = \frac{(V_{IN} - V_{SWITCH}) \times D_{MAX}^{***}}{L \times f_{SW}}$

*LIR is the ratio of the inductor ripple current to average continuous current at the minimum duty. cycle. Selecting an LIR in the 20% to 40% range is recommended to achieve the highest performance and stability.
**T_S is the switching period of the device and η is the efficiency.
***D_{MAX} is the maximum duty cycle.

The voltage stress on the switching transistor is usually not an issue in battery-powered converters. The 20V and 50V breakdown-voltage ratings for standard logic-level MOSFETs are adequate for the low-input and output voltages found in battery-powered systems.

Dissipation losses occur in the parasitic resistive elements of the regulator circuit. These losses include the series resistance of the battery; the equivalent series resistance (ESR) of the filter capacitors; the on-resistance of the switching element; and the resistances in the conductors, connectors, and wiring. Dissipation losses are proportional to the square of the peak current, so reducing the peak current can greatly minimize these losses. In addition, internal heating degrades a battery's chemistry; thus, excessive peak currents can shorten a battery's life.

Other Topologies

The buck regulator is the best choice for most battery-powered applications, provided you can afford the several cells needed to generate a battery voltage higher than the output voltage. Inductor current flows to the load during both phases of the switching cycle, so the average output current equals the average inductor current. In theory, the highest efficiency occurs when the input voltage is low, which implies fewer battery cells in series. Assuming the switch's on-state voltage drop is much smaller than the input voltage, a low input voltage reduces the AC switching losses and the RMS input current.

Boost, or step-up, topologies generate an output voltage that is greater than the input voltage. These topologies suit systems with a limited number of battery cells. Because the source voltage and the inductor are in series, the average inductor current equals the DC input current given by:

$$I = P_{IN}/V_{IN}.$$

Sometimes called the buck-boost circuit, the inverter topology generates an output voltage that has opposite polarity from the input voltage. Inverting and flyback regulators are electrically equivalent when considering peak currents and voltage stress. These topologies are most suitable for applications that require negative or galvanized isolated outputs. In general, however, the high peak currents make inverting and flyback topologies the least attractive of the simple regulators.

Inverting and boost topologies operate similarly, but the inverter's rectified inductor current produces a negative output voltage which is not aided by the source voltage. The inverting regulator's switching element experiences large voltage swings that impose high switching losses and stress on the transistor. In addition, inverting and flyback regulators have input and output filter capacitors that must absorb current waveforms with large, sharp transitions. Fast-moving waveform edges are absent at a boost regulator's input capacitor or a buck regulator's output capacitor.

Upside-Down Topologies Have Low-Side Switch

You can implement three negative topologies by connecting the classic buck, boost, and inverting topologies upside down. Because the input source is inverted, you must reverse the polarities for the switch and rectifier (Figure 1). Although there are no ICs currently available for the negative topologies, you can use a positive-output IC. Negative buck regulators have all the advantages of positive buck regulators, with the added benefit of a low-side switch. The low-side switch arrangement uses a low R_{ON} n-channel MOSFET with simple drive requirements. The negative buck regulator has some appeal as an alternative for the main positive regulator, as long as the battery can float with respect to system ground. If battery floating is possible, you can refer ground to the negative output and the battery's positive terminal to V_{OUT}.

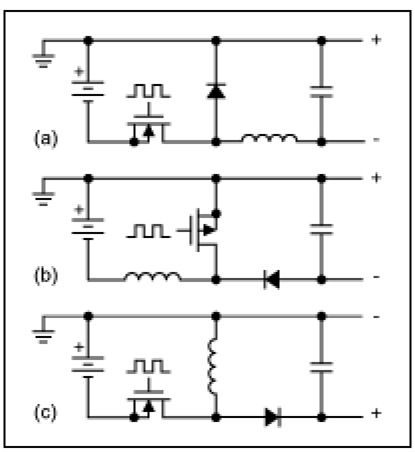


Figure 1. You can invert the input source to create three topologies. The negative buck regulator (a) has an output voltage less than the input. The negative boost regulator (b) has a more negative output than input. The negative-inverter regulator (c) converts a negative voltage to a positive voltage.

Usually, building several independent supplies is the best way to design multiple outputs in a battery-powered system. Using simple topologies, you can generate the remaining outputs using off-the-shelf transformers or charge-pump taps.

Coupled-inductor circuits (**Figure 2**) add an extra flyback winding to the basic buck, boost, and inverting topologies. These hybrid circuits are important, because they combine the advantages of a flyback circuit (isolation and inexpensive multiple outputs) with the benefits of the buck and boost circuits (low peak current and low voltage stress on the switch). The coupled-inductor circuit reduces the number of windings required by a flyback circuit by one. This reduction allows the use of an inexpensive 1:1 transformer to generate dual output voltages.

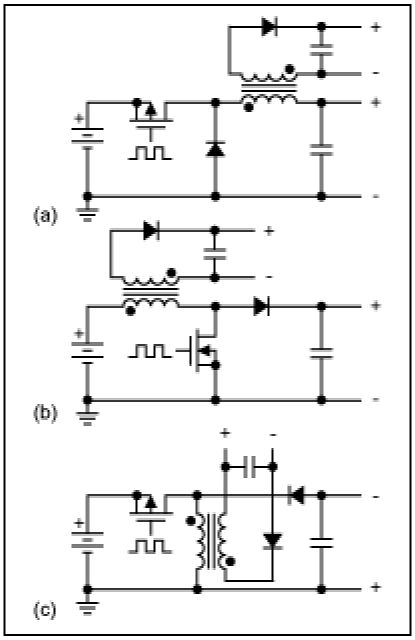


Figure 2. You can create auxiliary outputs by using a flyback transformer instead of an inductor in the basic (a) buck, (b) boost, and (c) inverter configurations.

The buck regulator with a flyback winding is the superior-performance topology for many battery-powered applications. The configuration has excellent stability, low peak currents, and low output ripple. The output power from the secondary winding depends on the main output's load current and the amount of differential voltage across the primary. Both of these parameters determine the change in core flux that triggers the flyback mechanism.

As a general rule, the total secondary power available is equal to, or less than, one-half the main output power. This guideline applies only to high input voltages. The estimate of secondary power should be reduced for input voltages less than one and one-half times the output voltage. The rule also does not apply to circuits that contain a synchronous rectifier instead of a simple diode. Synchronous rectifiers have a brief period when the primary current reverses, which causes the circuit to behave as a forward converter instead of a flyback converter. To efficiently transfer power during this forward conduction mode, you must minimize leakage inductance, reduce winding and rectifier impedance, and make the secondary output's filter capacitor as small as the ripple voltage will allow.

Diode-capacitor charge pumps offer another inexpensive way to generate multiple output voltages. Any node that has repetitive pulses can drive the diode-capacitor network. The gate-driver output or the main switching node of a switching regulator is a good candidate. Boost regulators, for example, can charge a flying capacitor through a grounded diode when the switching node is high (**Figure 3a**). Turning on the boost transistor forces the switching node and the flying capacitor's positive voltage end to 0V. When the boost transistor turns on, the flying capacitor generates a negative voltage by discharging into the auxiliary output capacitor.

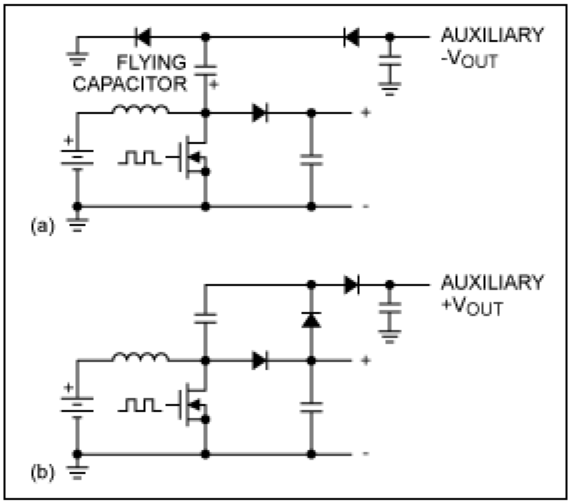


Figure 3. The charge-pump tap offers an inexpensive way to achieve an auxiliary output voltage. Tapping a boost circuit with a flying capacitor (a) creates a negative charge pump. Placing a voltage doubler on the output of a boost circuit (b) creates a high-voltage auxiliary output.

Diode-capacitor charge pumps work best with boost switching regulators, because the switching node swings between a well-defined voltage, V_{OUT}, and ground. Therefore, the line regulation is good. However, the regulation is not as good when you tap the switching node of a buck or inverting regulator, because the high voltage, V_{IN}, varies with battery voltage. Load regulation depends mostly on the diode's forward voltage drop. In very low-power applications (20mA or less) where an output powers an op amp or an FET-gate driver, you can build the charge pump using an inexpensive 1N4148 diode and a 1mF capacitor.

Part Selection Links
Switching Regulators for Battery Powered Applications
Charge Pump Regulators

Related Parts		
MAX15029	1.425V to 3.6V Input, 500mA Low-Dropout Regulators with BIAS Input	
MAX15059	76V, 300mW Boost Converter and Current Monitor for APD Bias Applications	Free Samples
MAX1595	Regulated 3.3V/5.0V Step-Up/Step-Down Charge Pump	Free Samples
MAX1806	500mA, Low-Voltage Linear Regulator in µMAX	Free Samples

MAX1846	High-Efficiency, Current-Mode, Inverting PWM Controller	Free Samples
MAX1935	500mA, Low-Voltage Linear Regulator in Tiny QFN	Free Samples
MAX8566	High-Efficiency, 10A, PWM Internal-Switch Step-Down Regulator	Free Samples

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