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A THREE-STEP PROCESS HELPS YOU SELECT THE RIGHT DESIGN FOR YOUR LOW-VOLTAGE APPLICATION AND EXAMINES THE LATEST LOW-DROPOUT AND SWITCHING-REGULATOR TECHNOLOGIES.

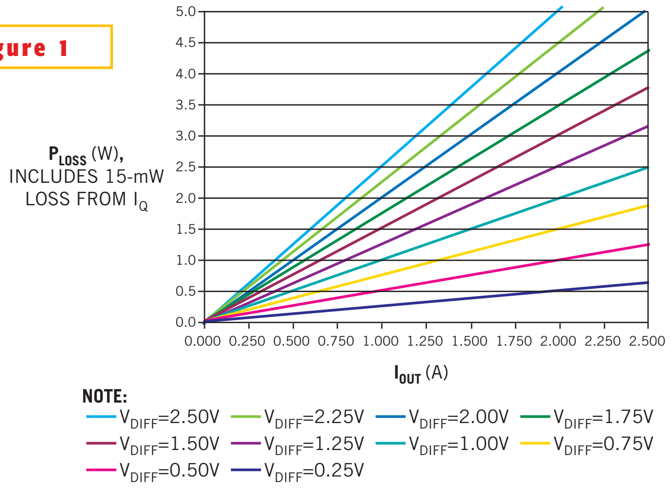
Powering your core voltage

As processor- and ASIC-core voltages continue on a downward spiral, selecting the best design to provide these lower voltages requires a thorough knowledge of both requirements and options. It's safe to say that most of us prefer to use linear regulators rather than switching regulators if we can get away with it. Linear, or LDO (low-dropout), regulators generally offer easier implementations, lower costs, and smaller footprints. Unfortunately, the power lost from reducing the voltage from V_{IN} to V_{OUT} results in lower efficiencies and greater heat, often eliminating the use of linear regulators as viable options. And, as V_{OUT} follows core voltages downward, the linear regulator may become even more difficult to qualify. However, immediately dismissing LDO regulators may be a mistake, given their many advantages.

After you evaluate linear regulators, you still need to explore all the switching-regulator options. Should you use a synchronous or an asynchronous part; current mode or voltage mode; pulse width, pulse frequency, or hysteretic switching? What other features do you need? Given the countless choices of linear and switching regulators, finding the right solution for your product may greatly depend on comparing a detailed list of your application requirements with the various available options. Keeping this idea in mind, step one in a three-step process to select the right design is to completely document and understand your needs by creating a thorough list of all your requirements, constraints, and desired features.

Start your list with the basics: input voltage, output voltage, and load current. From there, continue adding as much information as possible. The more requirements, constraints, and desired features you can provide to your list, the easier it will be to narrow down all of the available options. Use this list to remind yourself of what is important and help understand and justify your ultimate decision. Other items on your list may include cost, size, dropout voltage (minimum $V_{IN}-V_{OUT}$ differential), minimum/maximum input voltage, minimum/maximum acceptable load voltage, tolerance/accuracy,

Figure 1



For linear regulators, you can plot power loss versus I_{OUT} for a range of $V_{IN}-V_{OUT}$ differentials (V_{DIFF}).

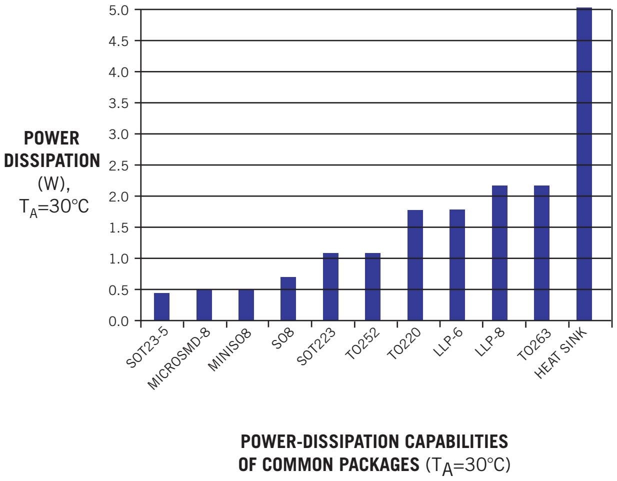


Figure 2 **Industry-standard packaging technology can provide more than 2.0W of power dissipation without a heat sink.**

Figure 3

The packages mentioned in Figure 2 appear in sequence and at relative scale.

load transients, line regulation, quiescent current, battery type and operating life, on/off pins, packaging/layout/placement constraints, sequencing, soft start, ambient temperature, desired and forbidden switching frequencies, and part-source/type restrictions. Besides these items, are there any other factors that may influence your ultimate decision?

After you thoroughly explore and document the requirements and restrictions, step two of the process is to investigate linear regulators as an option. This step is necessary because it is a quick and easy way to narrow down your options while examining the pros and cons of using a linear regulator. The most important calculations, which determine power loss, efficiency, and required heat dissipation are easy to compute: First, determine power loss by multiplying I_{OUT} by the $V_{IN}-V_{OUT}$ differential and then add to this figure the power consumed by the IC's internal circuitry: $P_{LOSS}=[(V_{IN}-V_{OUT})*I_{OUT}]+P_{IC}$, where $P_{IC}=V_{IN}*I_{GND}$ (also known as I_{SUPPLY} or I_Q).

Make sure you use V_{IN} maximum and V_{OUT} minimum to compute the worst-case figures. The power source usually specifies V_{IN} maximum, and you can determine V_{OUT} minimum using the accuracy listed in the datasheet. Next, calculate the amount of power you're delivering to the load by multiplying output voltage by the load current: $P_{OUT}=V_{OUT}*I_{OUT}$. Lastly, compute efficiency by dividing the output power given to the load by the total power given to the system: Efficiency$=P_{OUT}/(P_{OUT}+P_{LOSS})$. Now you know the key figures that usually qualify or eliminate linear regulators as an option.

Power loss leads to both heat generation and poor efficiency. A key question is whether you can dissipate and tolerate the heat and reduced battery life associated with the linear regulator. Another key question is whether you can improve the LDO regulator's performance to keep it as a potential option. **Figure 1** plots power loss versus I_{OUT} for a range of $V_{IN}-V_{OUT}$ differentials (V_{DIFF}). **Figure 2** illustrates the power-dissipation capabilities of several common packages. As you can see from **Figure 2**, industry-standard packaging technology can provide more than 2.0W of power dissipation without a heat sink. Compare this figure with your P_{LOSS} calculation. **Figure 3** illustrates the packages from **Figure 2** in sequence and at relative scale.

Knowing that load current and the $V_{IN}-V_{OUT}$ differential determine power loss, what can you do to improve the LDO regulator's performance and stay within standard packaging limits? Although the load itself sets output current and voltage, you may be able to decrease the input voltage and reduce V_{DIFF}. If you can reduce this differential, you reduce power loss and packaging constraints. As a result, more LDO-regulator solutions become available.

New LDO regulators have answered the call with ever-lower dropout voltages (V_{DIFF}) and methods to reduce the minimum input and output voltage floors. FETs are replacing bipolar transistors as pass transistors because the on-resistance of the FET can produce lower voltage drops than the bipolar's fixed saturation voltage (**Figure 4**). Unfortunately, most LDO regulators still require a minimum input voltage higher than necessary to run the control circuitry. Several LDO regulators have come to market with an improved method: They have both a V_{IN} and a V_{BIAS} input rail to separate the main current path from the IC bias path. In other words, the part's control circuitry runs off a higher standard voltage (5V) and minimal current (3 mA), and the high current path to the output comes from a separate, low-voltage input (V_{IN}). This setup reduces the $V_{IN}-V_{OUT}$ differential and the resulting power losses. An example of a circuit using a V_{BIAS} pin, National Semiconductor's LP3883, has a 210-mV dropout at 3A of output current. Here, you can supply 3A to your 1.2V load (3.6W) from a 1.5V source (another core voltage) and create only 900 mW of power loss. Add the 3 mA of current consumed by the control circuitry, which runs on 5V, and total power loss comes to 915 mW, which several package types can easily handle. Using these new LDO regulators, your best strategy may be to search out and capitalize on the lowest voltage on your board. If you can use a linear regulator in a standard package, it will often be cheaper, smaller, and easier to use than a switcher.

To determine power-dissipation re-

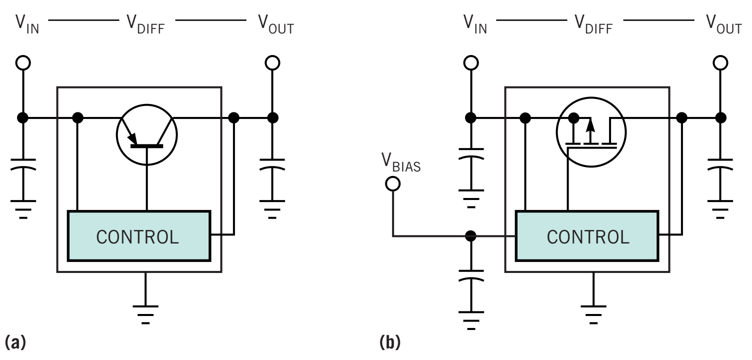


Figure 4

FETs are replacing bipolar transistors as pass transistors because the on-resistance of the FET can produce lower voltage drops than the bipolar's fixed saturation voltage.

quirements for your application, follow the formula $\theta_{JA}=(T_J-T_A)/P_{LOSS}$, where θ_{JA} is a package's thermal resistivity, T_J is the maximum junction temperature of the IC (usually, 125°C), and T_A is the ambient temperature of the IC's immediate surroundings (your system's internal environment). This example uses 30°C for T_A (86°F, or roughly room temperature) and 125°C for T_J. Once you've computed the θ_{JA} necessary for your solution, compare this figure with the packages listed on your LDO's datasheet. The θ_{JA} for the packages listed in the datasheet must be equal to or less than the required θ_{JA} determined from your calculations, or the junction temperature may exceed the specified maximum.

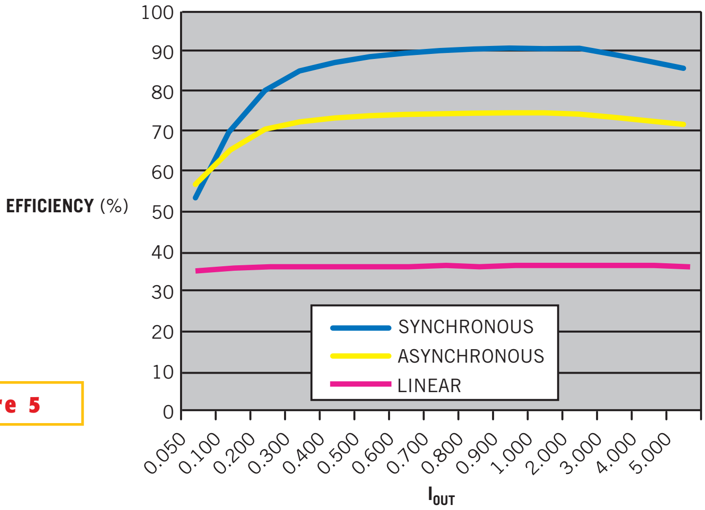
At this point, you've computed the power loss associated with using a linear solution and you've determined what kind of package you need to dissipate the heat. Now consider how power loss and efficiency affects battery life. Battery life is commonly specified in milliamp hours, or mAh. Loosely, you can say that a 100-mAh battery can provide 10 mA of current for 10 hours, or 100 mA for one hour. (Many factors can affect or reduce these figures.)

If the core requires 100 mA, the linear regulator must pass 100 mA of current through its pass transistor, regardless of the input or output voltages. However, a switching regulator can control the on time (duty cycle) of the pass transistor to reduce the average input current required from the source. Switchers are more efficient than LDOs in most cases because of this input current reduction, making them very attractive options for efficiency and heat-sensitive applications.

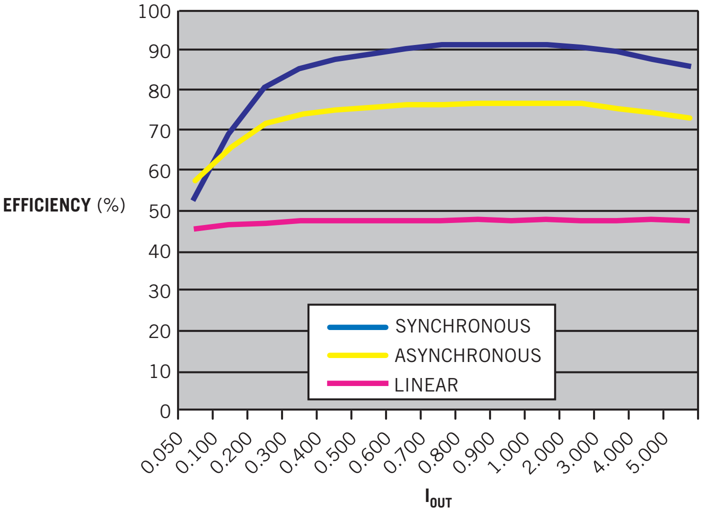
One final note about linear regulators: If the core voltage uses 1.2V, check to see whether it can tolerate higher voltages. Most of the linear regulators on the market use standard bandgap references, which limit the minimum output voltage to roughly 1.25V. Many more—and, usually, lower cost—regulator options will become available for designs that can tolerate higher voltages.

You now know the required efficiency, power loss, dropout, and package needed to implement a linear solution. Step three examines switching regulators. The new LDO regulators discussed earlier have drastically reduced dropout voltages, helping them in some cases approach

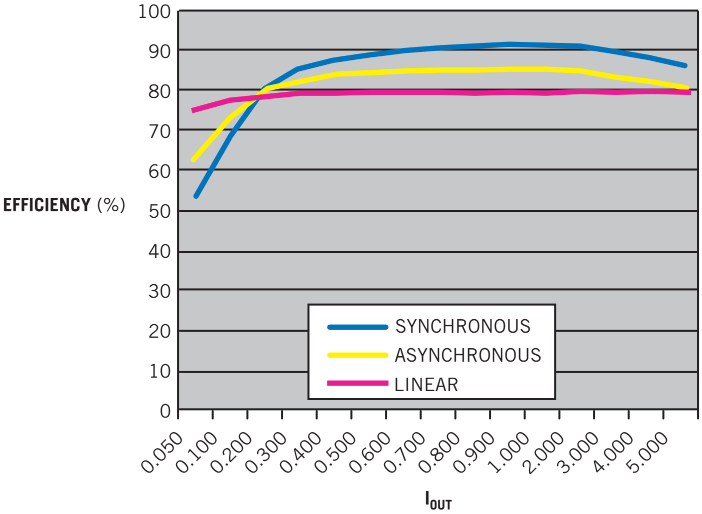
Figure 5



(a) **NOTE:** V_{IN}=3.3V, V_{OUT}=1.2V, V_{DIFF}=2.1V.



(b) **NOTE:** V_{IN}=2.5V, V_{OUT}=1.2V, V_{DIFF}=1.3V.



(c) **NOTE:** V_{IN}=1.5V, V_{OUT}=1.2V, V_{DIFF}=0.3V.

You can calculate efficiency curves for a synchronous switcher, an asynchronous switcher, and a linear regulator with a 1.2V output over a 50-mA to 5A current range.

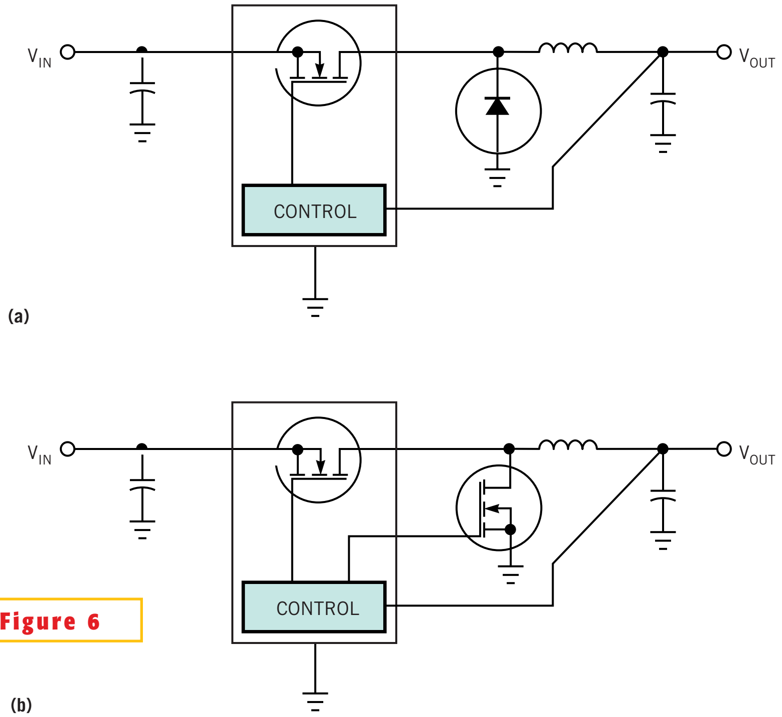


Figure 6

Asynchronous regulators use a transistor and a diode to complete the energy-transfer cycle. Synchronous regulators use two transistors.

switching-regulator efficiencies and broadening their use. However, switchers still offer better efficiencies overall, and there are many types to choose from.

To begin, take a look at how switcher efficiencies compare with linear regulators. **Figure 5** shows calculated efficiency curves for a synchronous switcher, an asynchronous switcher, and a linear regulator with a 1.2V output over a 50-mA to 5A current range. As you reduce the input voltage from 3.3V to 2.5 and 1.5V, the efficiencies of the asynchronous switcher and the linear regulator show considerable improvement. With the linear regulator, efficiency is roughly V_{OUT}/V_{IN}, so you see the efficiency increase from roughly 35 to 80% as the input decreases to 1.5V, approaching the efficiency of the switchers. The asynchronous switcher's efficiency increases roughly 10%, because, as the input voltage drops, the duty cycle increases, and more time is spent conducting through the pass transistor rather than the diode, which requires a larger, fixed voltage drop (0.5V in this example). Keep in mind that these efficiencies are theoretical. In actuality, the switcher's pass transistor and inductor voltage drop may prevent you from achieving 1.2V from 1.5V, making LDO regulators even more attractive at these levels.

Now, focus your attention on switcher efficiencies at low output voltages and the trade-offs between the two primary switcher categories: synchronous and asynchronous. Switchers are more efficient because they reduce the current required from the source. With linear regulators, the pass transistor is always on, and any excess energy ($V_{DIFF}*I_{OUT}$) is dissipated in the form of heat. However, switching regulators store this excess energy using an inductor and a capacitor at its output. The load then drains this energy until the next switching cycle refreshes it. Because switching regulators store rather than waste excess energy, they reduce the average input current, resulting in improved efficiency.

Asynchronous regulators use a transistor and a diode to complete the energy-transfer cycle (**Figure 6**). During the first part of the cycle, the transistor passes energy from the source to the load and the LC filter. Once this transistor is off, the diode forward-biases to allow energy to flow from the LC storage and feed the load for the remainder of the cycle. Because diodes require a significant voltage (0.4V) to remain forward-biased, it's best to use the pass transistor as much as possible to increase efficiency. Unfortunately, low output voltages usually create short duty cycles.

Synchronous regulators replace the asynchronous diode with another transistor. This transistor has a lower voltage drop than the diode, resulting in better efficiency than asynchronous switchers. An exception is during light loads, when the low on-resistance adds little to system efficiency, yet you must still switch the synchronous FET on and off. **Figure 5** shows this effect. As I_{OUT} approaches 0A, the synchronous-FET switching losses significantly reduce efficiency.

In general, synchronous regulators are still more efficient than asynchronous regulators for applications in which you need low duty cycles, high output currents, or low output voltages—all of which may pertain to supplying your core voltage.

Many switchers include features to improve synchronous-regulator efficiency during light loads. Some skip pulses or reduce the switching frequency so that they switch less often. Another method is to disable the synchronous-FET driver, using an asynchronous diode in parallel with the synchronous FET to complete the path. This method results in asynchronous efficiencies during light-load operation and synchronous efficiencies during normal operation. Of course, each feature may add complexity, cost, or size. It is vital that you compare these options with your list of requirements and constraints.

What is most important to your design: efficiency, cost, or size? Unfortunately, computing switcher efficiency, cost, and size is much more complex than computing those values for linear regulators. A good place to start is with general efficiency graphs, such as in **Figure 5**, to identify which approach suits your efficiency requirements. Knowing your cost and size limits is vital. High switching frequencies result in smaller inductors and capacitors, which can reduce the overall footprint and solution cost. However, increased switching frequencies may also reduce your design's overall efficiency.

Because so many choices exist, you should enlist the help of several linear- and switching-regulator suppliers. Given your list of requirements, they should be able to quickly identify a list of possible approaches and may give you access to new parts that have yet to be publicly released. Once you narrow the options, you can calculate efficiency, cost, and size and compare these qualities with the other potential options—again using the supplier's support and tools. Also keep in mind that, although new switchers may include sub-bandgap references, most of them still use standard bandgap references. This usage limits the minimum output voltage of most switchers to at least 1.25V.

The switched-capacitor converter deserves honorable mention. Switched capacitors can provide more efficient approaches than can linear regulators without using an inductor. However, they are current-limited to approximately 300 mA. Switched-capacitor designs have been most attractive in battery-powered applications, in which inductor size and EMI have been major deterrents. However, new switcher and inductor technologies have made switching regulators more attractive in many of the applications that once used switched-capacitor converters.

Several options exist for powering low-voltage cores. Step one in the three-step process is to create a complete list of requirements and constraints. Step two is to analyze the linear regulator as a possible approach, taking into account new LDO-regulator and standard-packaging technologies. And step three is to examine switching regulators and the efficiency trade-offs among synchronous, asynchronous, and linear solutions. Using your list of requirements and the information you've gathered, contact several suppliers to enlist their help in narrowing down options and computing solution efficiency, cost, and size. They'll be eager to hear from you.□

AUTHOR'S BIOGRAPHY

Jason Rubadue received a BSEE from the University of Washington and has worked with National Semiconductor since 2000. His interests include running, snowboarding, hobby robotics, and traveling. You can reach him at Jason.Rubadue@nsc.com.