Linear versus switching regulators in industrial applications with a 24-V bus

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Figure 1. Switching (buck) converter with integrated MOSFETs

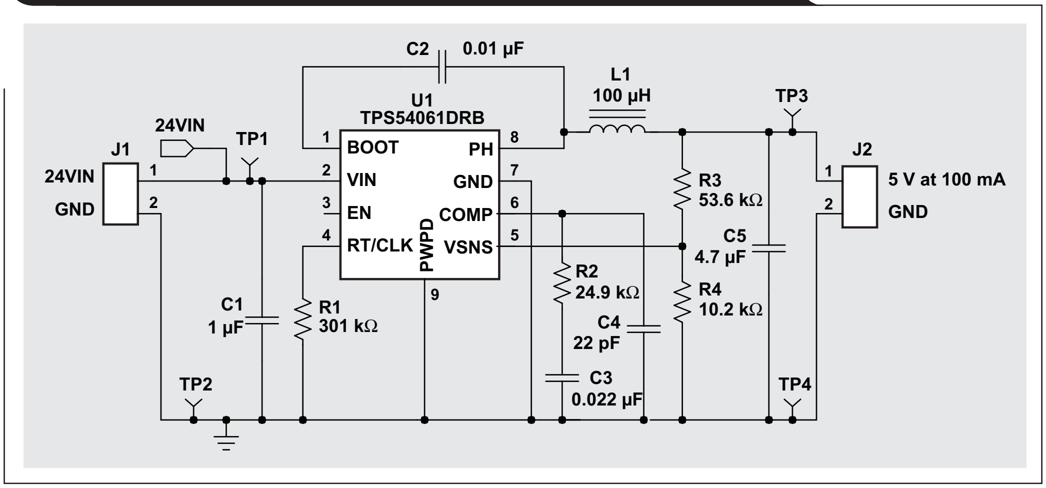
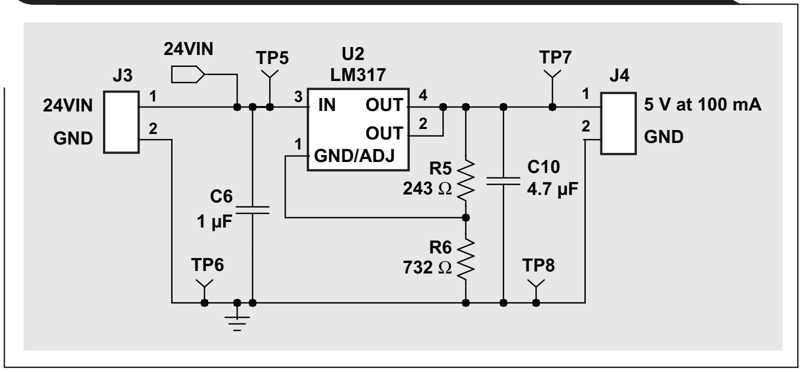


Figure 2. Integrated, wide-input-voltage linear regulator



Linear regulators have been around for many years. Some designers still use linear regulators that are over 20 years old for new and old projects. Others have made their own linear regulators from discrete components. The simplicity of a linear regulator is hard to beat for a wide range of voltage conversions. However, low-current applications with a 24-V bus, such as for industrial automation or HVAC controls, may have thermal issues if the voltage drop is too large. Fortunately, designers have several choices now that small, high-efficiency, wide-input-voltage switching regulators are available.

This article compares three different solutions that provide a 5-V output at 100 mA from a 24-V bus. A synchronous step-down (buck) converter is compared to an integrated linear regulator and a discrete linear regulator. Size, efficiency, thermal performance, transient response, noise, complexity, and cost are compared to help designers choose the solution that best meets the constraints of a particular application.

Conditions of comparison

Most industrial applications use a 24-V bus and require 5 V to power various loads, such as logic and low-current microprocessors. An output current of 100 mA is chosen because it accommodates many logic and processor loads. However, the power-dissipation level can affect the decision of whether to use a switching or linear regulator. The circuits shown in Figures 1, 2, and 3 are all built on the same circuit board and use 1-µF input and 4.7-µF output ceramic capacitors with the same ratings.

The design in Figure 1 uses a synchronous buck converter with integrated MOSFETs, the TPS54061 from Texas Instruments (TI). Note that this circuit does not require a catch diode but includes an inductor, five capacitors, and four resistors. The device also employs external compensation and is tuned to use the same input and output capacitors as the linear circuits in Figures 2 and 3.

The design in Figure 2 uses an integrated, wide-input-voltage linear regulator, TI's LM317, which is a popular, industry-standard regulator with a 1.5-A output capability. This circuit uses two external resistors and two external capacitors. The wide difference between the input and output voltages requires the low thermal resistance of a double-decawatt package (DDPak).

Figure 3. Discrete linear regulator

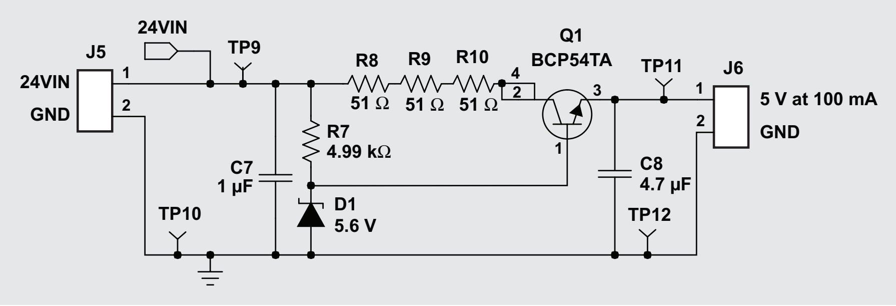


Figure 3 shows a discrete linear regulator that employs a transistor and a Zener diode with two external capacitors and four external resistors. The Zener diode breaks down at 5.6 V, and that voltage is fed to the base of an NPN transistor. Due to the base-emitter voltage drop, the output is regulated to ~5 V. The external resistors are used to help with the power dissipation in the NPN transistor.

Table 1 summarizes the board area and component count of each design.

Linear-regulator solutions require more board area to provide proper thermal relief on the circuit board. At full load, each linear-regulator solution must dissipate about 2 W. As a rule of thumb, approximately 1 W of dissipation in 1 in^2 of board area results in a 100°C temperature rise. The linear-regulator solutions are designed to allow for a 40°C temperature rise. The synchronous buck converter is clearly the design of choice when board area is limited, despite the number of external components and the design effort required to compensate the feedback loop and select the inductor.

Table 1. Summary of board area and component count

REGULATOR TYPE	BOARD AREA (in^2)	NUMBER OF COMPONENTS	COMPLEXITY
Switching (Buck) (TPS54061)	0.14	11	High
Integrated Linear (LM317)	2.25	5	Low
Discrete Linear (Zener/Transistor)	2.25	8	Medium

Table 2. Summary of thermal performance

REGULATOR TYPE	TEMPERATURE RISE (°C)	MAXIMUM TEMPERATURE (°C)	PACKAGE
Switching	11	40.7	3×3-mm VSON
Integrated Linear	27	56.2	DDPak
Discrete Linear	40	69.1	SOT-23, SOT223

Thermal performance

The thermal image in Figure 4 shows the temperature rise of each design on the circuit board. The board is designed in a manner such that none of the circuits disturb the thermal performance of an adjacent circuit. Table 2 shows that the switching regulator has the lowest temperature rise, at 11°C. With a large difference between the input and output voltages, the switching regulator with synchronous rectification excels in efficiency compared to either

Figure 4. Heat generated from each circuit (white indicates highest temperature)

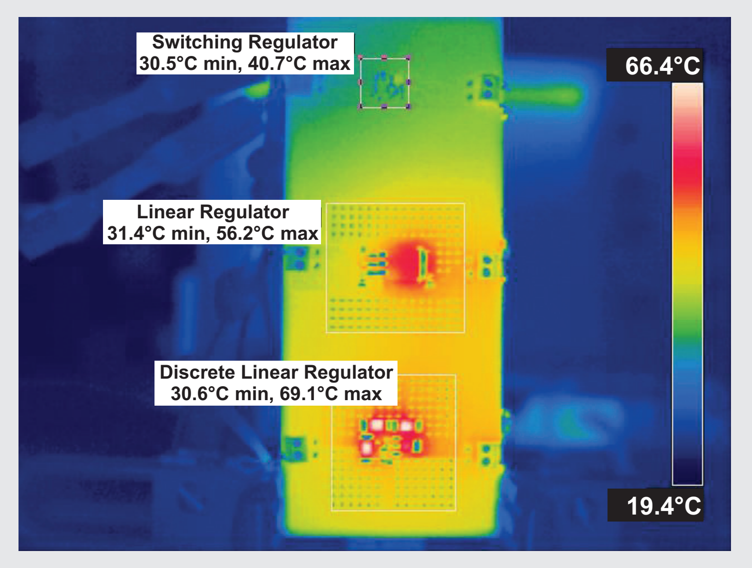


Table 3. Summary of efficiency and power loss

REGULATOR TYPE	MAXIMUM LOAD EFFICIENCY (%)	MAXIMUM LOAD POWER LOSS (W)	NO LOAD QUIESCENT CURRENT (mA)
Switching	84.5	0.093	0.5
Integrated Linear	20.0	2.06	5.5
Discrete Linear	20.1	2.02	4

linear circuit. (See Table 3.) It is interesting to note that the temperature rise of the integrated linear circuit is different from that of the discrete linear circuit. Since the integrated linear regulator's package (DDPak) is larger, its dissipated heat is spread over more area. The discrete linear circuit using the SOT-23 and SOT223 packages is smaller than the DDPak and has a higher package power-dissipation rating, which makes dissipating the heat more difficult.

Efficiency comparison

The thermal performance is directly related to the efficiency of each regulator. Figure 5 shows an efficiency comparison of all three circuits. As expected, the switching regulator excels at both light-load and full-load efficiency. At light loads, switching losses and quiescent-current losses become more pronounced, which explains the reduced efficiency at lighter loads. At light loads, it is better to view the power-loss graph (Figure 6) than the efficiency graph, since a 50% difference in efficiency at 10 mA seems like a large margin. However, the amount of current consumed by the load is small. When the input voltage is 24 V and the output current is 10 mA, the power loss of the switching regulator is 2.8 mW, and the loss of the integrated linear regulator is 345 mW. At full load, the measured power dissipated is 0.093 W for the switching regulator versus 2.06 W for the linear regulator, which shows a wide margin and a drastic improvement.

Table 3 summarizes the efficiency and power loss of all three circuits. Note that the quiescent current of the discrete linear circuit is lower than that of the integrated linear circuit. The integrated linear regulator has more power-consuming internal circuitry and incorporates more features than the discrete linear circuit.

Figure 5. Efficiency versus load current

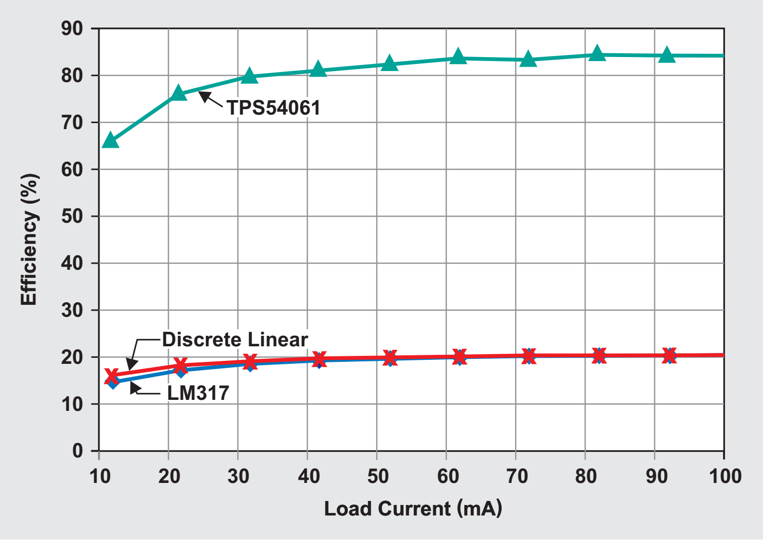
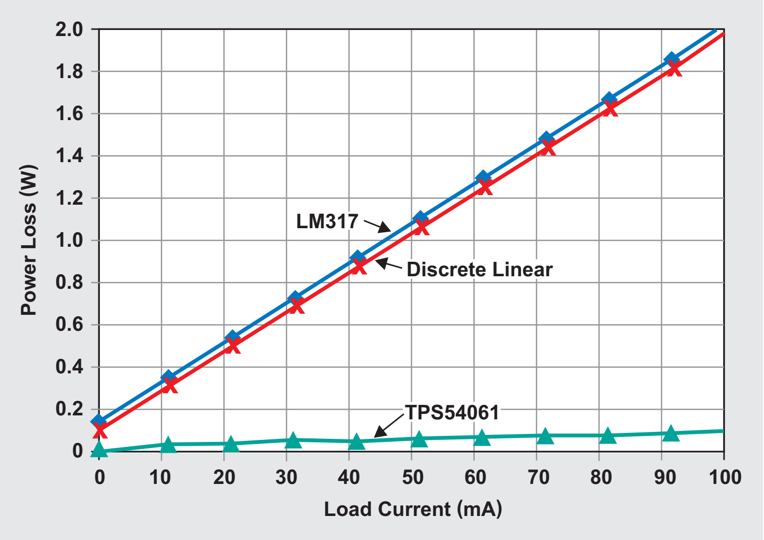


Figure 6. Power loss versus load current



Output-voltage characteristics

Analog circuits may be sensitive to voltage ripple, and digital processors may be sensitive to the accuracy of the core voltage. It is important to check the power supply's voltage ripple, voltage-regulation accuracy, and voltage-peak deviations during load transients. Linear regulators inherently have low ripple and are used to remove noise from switching regulators. The voltage ripple of both the integrated and the discrete linear-regulator circuits under maximum load is under 10 mV. When expressed as a percentage of the output voltage, accuracy is better than 0.2%. On the other hand, the voltage ripple of the switching regulator is 75 mV, or 1.5% of the output voltage. The low equivalent series resistance of the switching regulator's ceramic output capacitor allows for the circuit's low ripple, despite the switching regulator's inherent noise.

Comparing the output-voltage accuracy of the switching and linear regulators from no load to full load shows that the switching regulator has better performance. Further inspection of the product specification tables reveals that the reference voltage of the switching regulator is the most accurate of the three circuits. The switching regulator is a relatively new integrated circuit, and DC/DC converters are trending towards higher reference-voltage accuracies. The discrete linear circuit, which uses a simpler method for regulating the output voltage, has the worst performance. In many cases, applications do not need high voltage accuracy since the 5-V output may be postregulated.

The load-transient plots can be seen in Figures 7 through 9. Although the switching regulator has high output-voltage accuracy, its measured peak-to-peak voltage during a load transient is not as competitive as that of the linear circuits. The switching regulator's measured peak-to-peak voltage during a 50- to 100-mA load step is 250 mV, or 5% of the output voltage, compared to 40 mV for the linear circuits. Additional output capacitance can be added to the switching regulator to reduce the voltage peaks, but with penalties in cost and size. Note that the discrete linear circuit is not designed to attempt recovery of the output voltage during a load transient. Also, the simplicity of the circuit does not allow for current limiting or thermal-shutdown protection!

Figure 7. Switching regulator during load transient

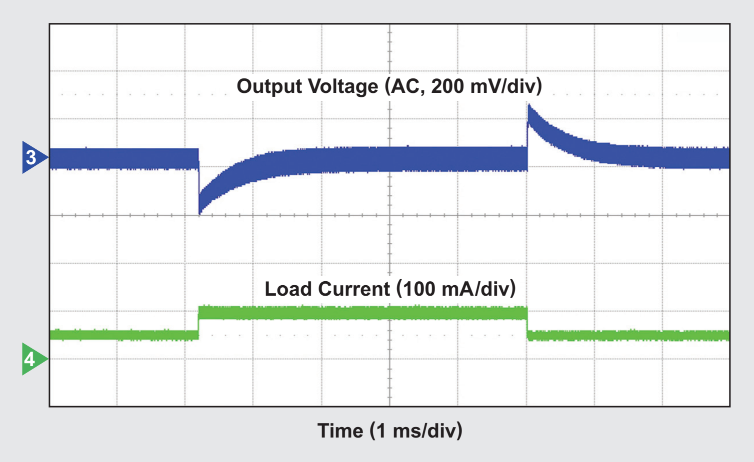


Figure 8. Integrated linear regulator during load transient

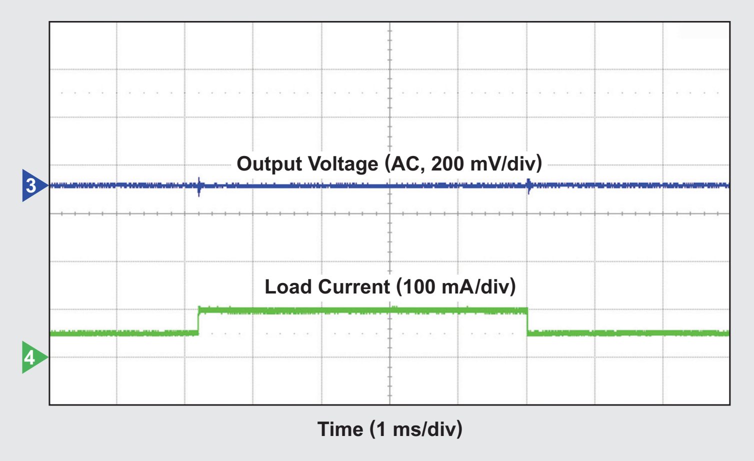


Figure 9. Discrete linear regulator during load transient

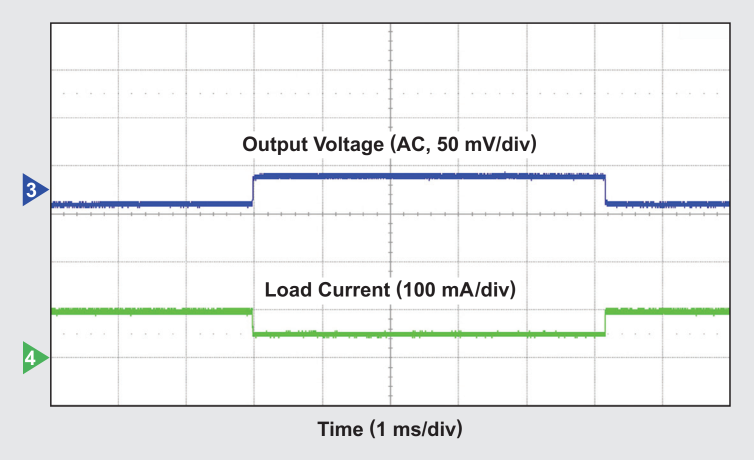


Table 4 summarizes the output-voltage characteristics of the three regulator designs.

Cost comparison

Most of the external components used in these circuits are small, passive resistors and capacitors that cost well below \$0.01. The highest-cost component of the three circuits is the silicon. Costs for all three bills of materials (BOMs), shown in Table 5, were collected from U.S. distribution channels at 10,000-unit suggested resale pricing. As can be seen, both linear-regulator solutions cost much less than the switching regulator. Unfortunately, the switching regulator requires an external inductor, which can cost about \$0.10; but the improvement in efficiency and size may be worth the additional cost. The cost difference between the integrated and discrete linear circuits is only \$0.06! The protection features alone may prove the value of the integrated over the discrete linear regulator.

Conclusion

There are many power-management solutions available to designers, and the best solution depends on the particular needs of the application. Power-management solutions that reduce energy consumption and save board space allow designers to make their products more differentiated and attractive on the market. A synchronous buck converter offers drastic improvements in efficiency and board space compared to either linear circuit. If a design must have the absolute lowest cost, a discrete linear circuit can help, but the trade-off is worse performance with potential penalties, such as the additional cost of heat sinking and the lack of protection features.

Table 6 summarizes the characteristics of all three regulator designs to aid the designer in choosing the best solution for a given application.

References

1. “3-terminal adjustable regulator,” LM317 Datasheet. Available: www.ti.com/slvs044-aaj
2. “Wide input 60V, 200mA synchronous step-down DC-DC converter with low IQ,” TPS54061 Datasheet. Available: www.ti.com/slvsbb7-aaj

Related Web sites

Power Management:
www.ti.com/power-aaj

www.ti.com/lm317-aaj
www.ti.com/tps54061-aaj

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Table 4. Summary of output-voltage characteristics

REGULATOR TYPE	MAXIMUM LOAD RIPPLE (mV)	OUTPUT TRANSIENT WITH 50- TO 100-mA LOAD STEP (mV)	REGULATION ERROR WITH 0- TO 100-mA LOAD STEP (mV)
Switching	75	250	1.5
Integrated Linear	<10	40	0.7
Discrete Linear	<10	40	21.8

Table 5. Summary of BOM cost

REGULATOR TYPE	BOM COST AT 10-ku RESALE PRICE (U.S. DOLLARS)
Switching	1.80
Integrated Linear	0.32
Discrete Linear	0.26

Table 6. Characteristics of 5-V/100-mA regulators with a 24-V input

REGULATOR TYPE	BOM COST AT 10-ku RESALE PRICE (U.S. DOLLARS)	V_{OUT} RIPPLE (mV)	FULL-LOAD EFFICIENCY (%)	BOARD AREA (in^2)	COMPLEXITY
Switching	1.80	75	84.5	0.14	High
Integrated Linear	0.32	<10	20.0	2.25	Low
Discrete Linear	0.26	<10	20.1	2.25	Medium

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