Discrete design of a low-cost isolated 3.3- to 5-V DC/DC converter

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Isolated 3.3- to 5-V converters are often required in long-distance data-transmission networks, where the bus-node controller operates from a 3.3-V supply to conserve power while the bus voltage is 5 V to maintain signal integrity and to provide high drive capability over long distances. Although isolated DC/DC converter modules for 3.3- to 3.3-V and 5- to 5-V conversion are readily available on the market, 3.3- to 5-V converters in integrated form are still hard to find. Even if a search for the latter proves successful, these specific converters—in particular, those with regulated outputs—often possess long lead times, are relatively expensive, and are usually limited to certain isolation voltages.

A discrete design can be a low-cost alternative to integrated modules if an application requires isolation voltages higher than 2 kV, converter efficiency higher than 60%, or reliable availability of standard components. The drawback of designing a discrete DC/DC converter is that it requires a great deal of work—choosing a stable oscillator structure and break-before-make circuit, selecting good MOSFETs that can be driven efficiently by standard logic gates, and performing temperature and long-term-reliability tests. This entire effort costs time and money. Therefore, before rushing into such a project, the designer should consider the following: Integrated modules have usually passed temperature tests and have met other industrial qualifications. These modules not only represent the most reliable solution but also provide a fast time to market.

Converters with unregulated output are priced at around \$4.50 to \$5.00 each in quantities of 1000 units, while converters with regulated output often cost twice as much, approximately \$10.00 or more. Thus, it makes sense to purchase a converter with unregulated output and either buffer the output with bulk capacitance or feed it into a low-cost, low-dropout regulator (LDO) such as the Texas Instruments (TI) TPS76650 at around \$0.50.

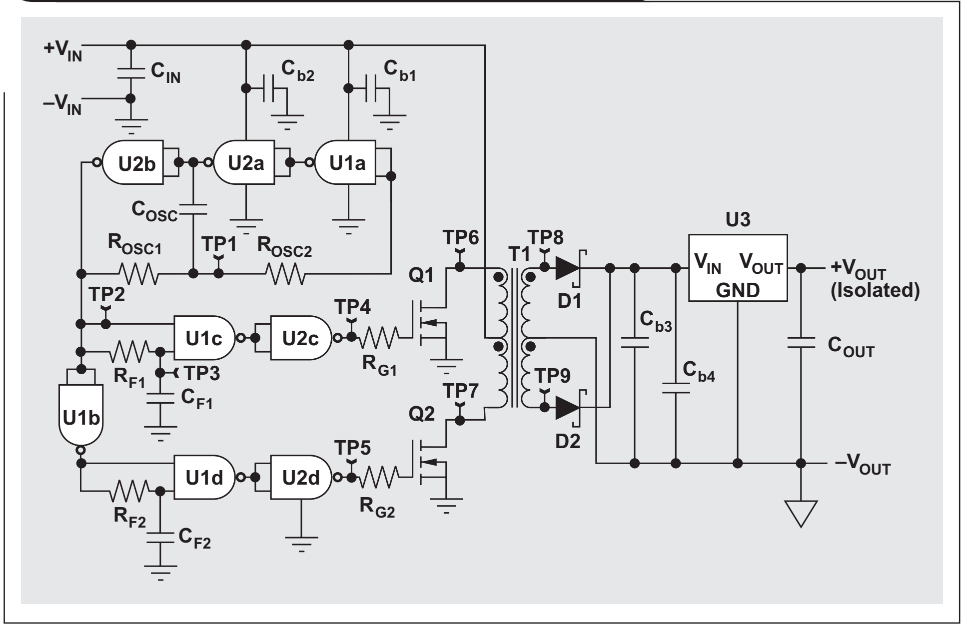
The discrete DC/DC converter design in Figure 1 uses only readily available, standard components (such as logic ICs and MOSFETs) for the transformer driver and an LDO for a regulated output voltage. While this circuit has been prototyped with through-hole components, thus making its form factor larger than that of integrated modules, the board space can be drastically reduced by using TI's Little Logic™ devices.

The main benefits of this design are its low bill of material (BOM) and the freedom to choose an isolation transformer for isolation voltages ranging from 1 to 6 kV. The goal is to offer a low-cost alternative to fully integrated DC/DC converters with regulated outputs, and to stand-alone transformer drivers (usually priced at around \$1.80), by making the transformer-driver stage as inexpensive as possible.

Operation principle

Low-cost, isolated DC/DC converters are commonly of the push-pull driver type. The operation principle is fairly simple. A square-wave oscillator with a push-pull output stage drives a center-tapped transformer, whose output is rectified and made available in regulated or unregulated DC form. An important, functional requirement is that the square wave must have a 50% duty cycle to ensure

Figure 1. Isolated 3.3- to 5-V push-pull converter



symmetrical magnetization of the transformer core. Another requirement is that the product of magnetizing voltage (E) and magnetizing time (T), known as the ET product and measured in Vµs, must not exceed the transformer's characteristic ET product specified by its manufacturer. A break-before-make circuit following the oscillator must also be implemented to prevent the two legs of the push-pull output stage from conducting simultaneously and causing a circuit failure.

The discrete design

The well-known three-inverter-gate oscillator, consisting of U1a, U2a, and U2b, has been chosen because it is stable with supply variations. Its nominal frequency is set to 330 kHz through a 100-pF ceramic capacitor (C_{OSC}) and two 10-kΩ resistors (R_{OSC1} and R_{OSC2}). The oscillator possesses a duty cycle of close to 50% and a maximum frequency variation of less than ±1.5% across a 3.0- to 3.6-V variation in supply voltage. Figure 2 shows the waveforms at the summing point of R_{OSC1} and R_{OSC2} (TP1) and at the oscillator output (TP2). All voltages are measured with respect to circuit ground.

Two Schmitt-trigger NAND gates (U1c, U1d) perform a break-before-make function to avoid overlapping of the MOSFET's conducting phases. Two other NAND gates (U2c, U2d) are configured as inverting buffers, generating the correct signal polarity necessary to drive the n-channel MOSFETs (Q1, Q2). The complete break-before-make action is shown in Figure 3. To accommodate the limited drive capability of standard logic gates, the MOSFETs have been selected for their low total charge and their fast response times.

The isolation transformer (T1) has a secondary-to-primary winding ratio of 2:1, a primary inductance of 0.9 mH, and a guaranteed isolation voltage of 3 kV. The input and output waveforms of the transformer are shown in Figure 4.

Figure 2. Oscillator waveforms at TP1 and TP2

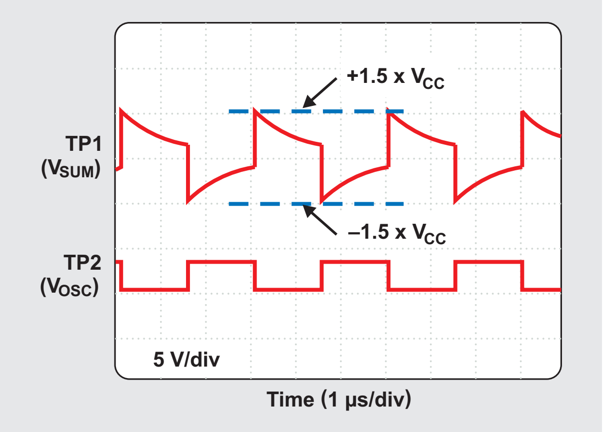


Figure 3. Break-before-make waveforms

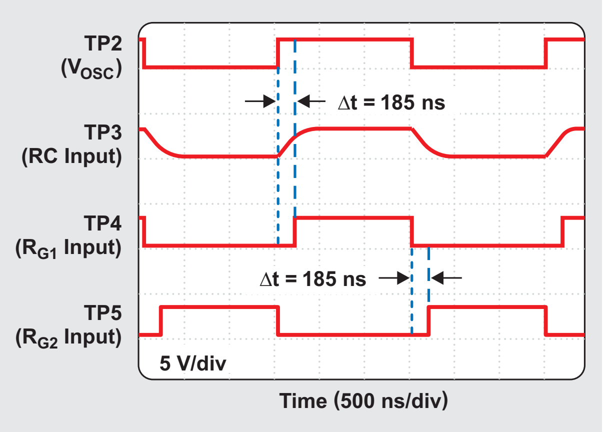
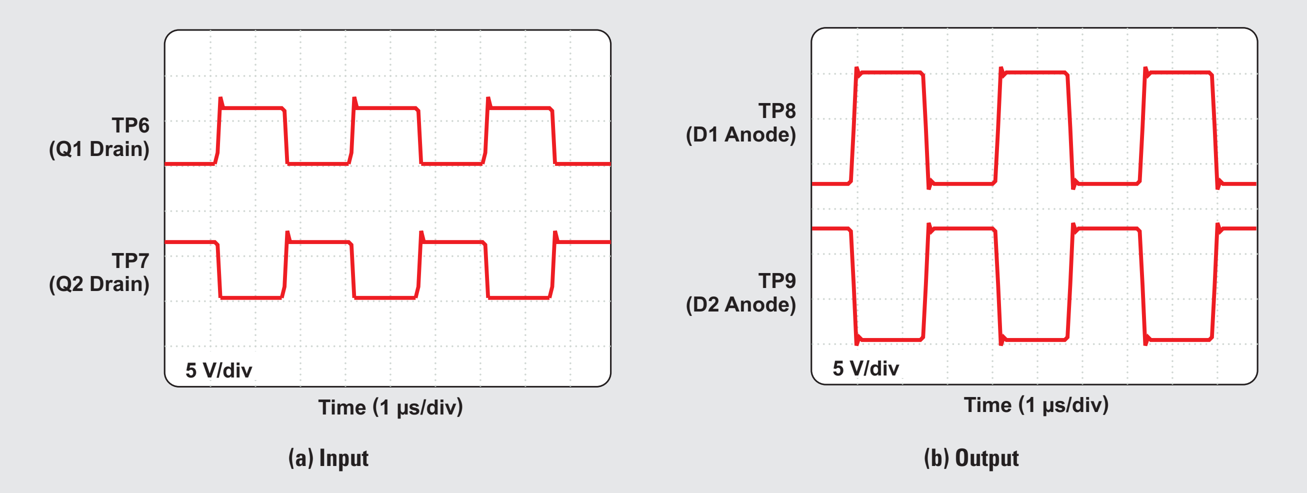


Figure 4. Transformer waveforms



(a) Input (b) Output

The two diodes (D1, D2) are fast Schottky rectifiers performing a full-wave rectification while providing low forward voltage at full load current ($V_{FW} < 0.4$ V at 200 mA). It is possible to take the output voltage directly from a bulk capacitor (Cb3) following the diodes. In this case, the output is unregulated but provides the maximum efficiency of the DC/DC converter. However, the designer must ensure that the maximum supply of the affected circuitry is not exceeded, which can easily occur under low-load or open-circuit conditions. If the unregulated output voltage under minimum load proves to be too high, it is necessary to use a linear regulator after the full-wave rectifier to provide a stable output supply.

The main benefit of a linear regulator is the low ripple output. Other benefits include short-circuit protection and overtemperature shutdown. The main drawback, however, is a significantly reduced efficiency.

Figure 5 shows the ripple of the circuit in Figure 1 at an output voltage of 4.93 V, and Figure 6 compares the circuit's efficiency with that of an integrated DC/DC module with regulated output.

Table 1 on the next page provides an approximate BOM for the discrete converter. Note that the values of the bypass capacitors are larger than the 10 nF commonly implemented in low-speed applications. This is because high-speed CMOS technologies such as AHC, AC, and LVC possess high dynamic loading, so the values for bypass capacitors must be 0.1 µF or higher to assure proper operation. This is of particular importance for the inverter buffers driving the MOSFETs, where the bypass capacitor is 0.68 µF.

Conclusion

Where board-space constraints are not an issue, the discrete design of an isolated 3.3- to 5-V DC/DC converter with regulated output can present a viable low-cost alternative to an integrated DC/DC module with regulated output. A major benefit of the discrete design is the freedom to choose an isolation transformer for varying isolation-voltage requirements.

Related Web sites

power.ti.com

www.ti.com/sc/device/*partnumber*

Replace *partnumber* with SN74AC00, SN74AHC132, or TPS76650

Figure 5. Output ripple at V_{OUT} = 4.93 V

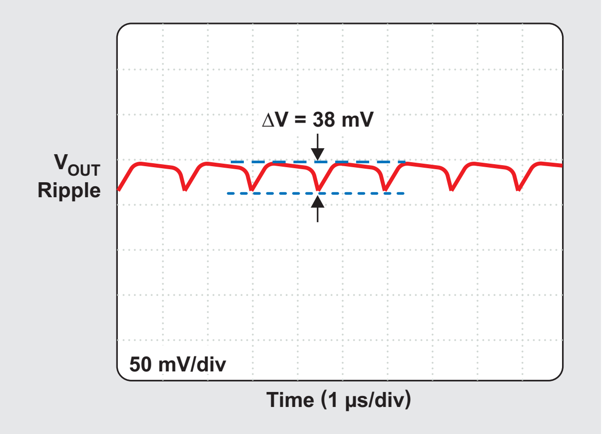


Figure 6. Efficiency comparison

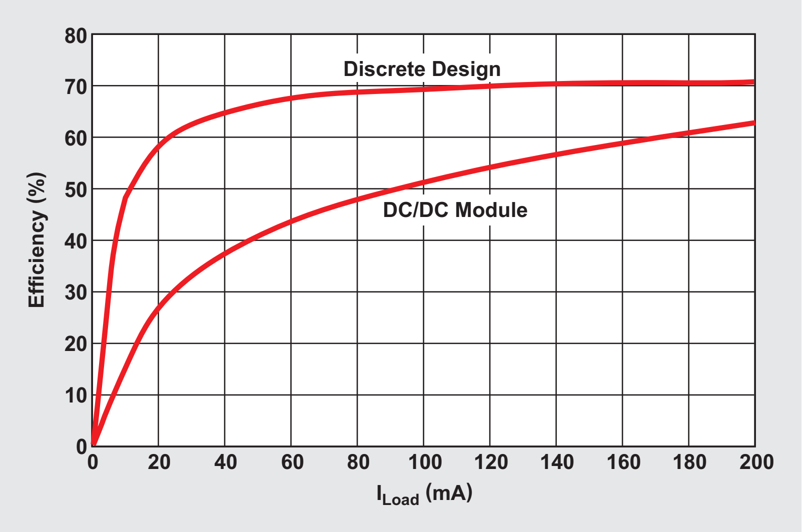


Table 1. BOM for discrete DC/DC converter

DEVICE LABEL	PART NUMBER OR VALUE	DESCRIPTION	COMPONENT PRICE* (EACH)	QUANTITY	TOTAL PRICE*	TRANSFORMER DRIVER PRICE*
U1	SN74AHC132	Quad Schmitt-trigger NAND	0.17	1	0.17	0.17
U2	SN74AC00	Quad NAND	0.17	1	0.17	0.17
U3	TPS76650	250-mA LDO	0.53	1	0.53	—
Q1, Q2	FDN335	n-channel power MOSFET	0.105	2	0.21	0.21
R_{OSC1}, R_{OSC2}	10 kΩ	OSC resistor	0.04	2	0.08	0.07
R_{F1}, R_{F2}	1.54 kΩ	Delay resistor	0.035	2	0.07	0.07
R_{G1}, R_{G2}	150 Ω	Gate-drive resistor	0.035	2	0.07	0.07
C_{OSC}	100 pF	Oscillator capacitor	0.04	1	0.04	0.04
C_{F1}, C_{F2}	47 pF	Delay capacitor	0.04	2	0.08	0.08
C_{b1}	0.1 µF	Bypass capacitor	0.02	3	0.06	0.02
C_{b2}	0.68 µF	Bypass capacitor	0.03	1	0.03	0.03
C_{b3}	0.1 µF	LDO input capacitor	0.02	1	0.02	—
C_{IN}, C_{b4}, C_{OUT}	4.7 µF	Bulk capacitor	0.12	3	0.36	0.12
D1, D2	MBR0520L	Schottky diode	0.045	2	0.09	—
T1	TGRTI-360NARL	1:2 transformer, 3 kV	2.31	1	2.31	—
				TOTAL	**4.28**	**1.09**

*Typical price in U.S. dollars in quantities of 1000 units.

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