Design for a Discrete Charge Pump

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ABSTRACT

Many applications require an auxiliary power supply in addition to a primary power supply. For example, TFT-LCD applications can require +20 V to +30 V and +10 V to +20 V. As a result of cost, board space, or inventory, a separate converter may not be appropriate for some applications. This document demonstrates a simple charge pump circuit that provides the auxiliary positive voltage using the TPS61087, a step-up dc-dc converter (also called a boost converter) from Texas Instruments.

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1 Step-Up Converter Waveforms

An overview of the voltage and current waveforms of a step-up converter help to provide an understanding of the typical *boost converter + charge pump* configuration. Figure 1 shows the TPS61087 with the necessary external parts. The TPS61087 is a single step-up converter with a 2-A switch current limit.

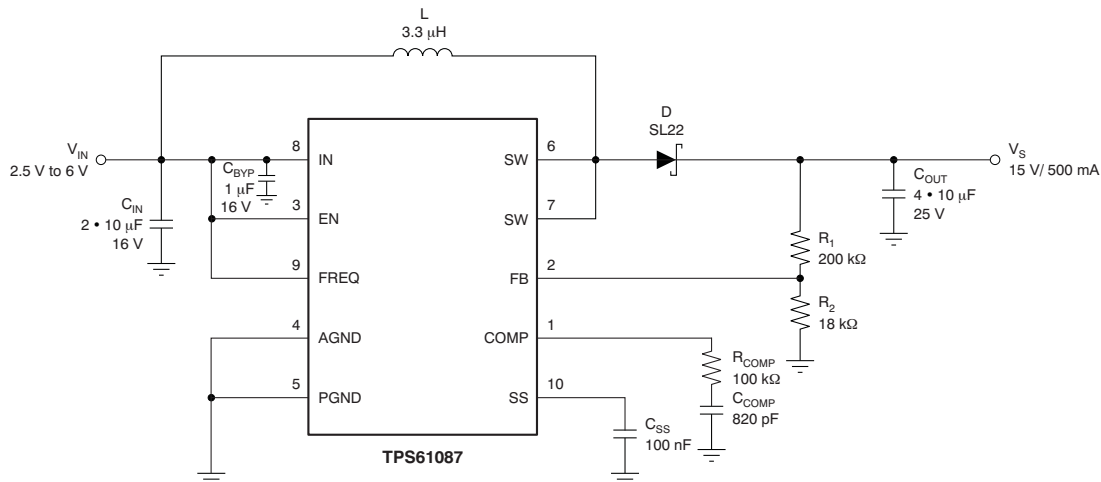**Figure 1. TPS61087 in Boost Converter + Charge Pump Configuration**

In continuous conduction mode, the converter switches with a fixed frequency. The waveforms shown in Figure 2 present the switch node voltage (V_{SW}), output ripple (V_{S_AC}), and inductor current (I_l) for the TPS61087 in continuous conduction mode.
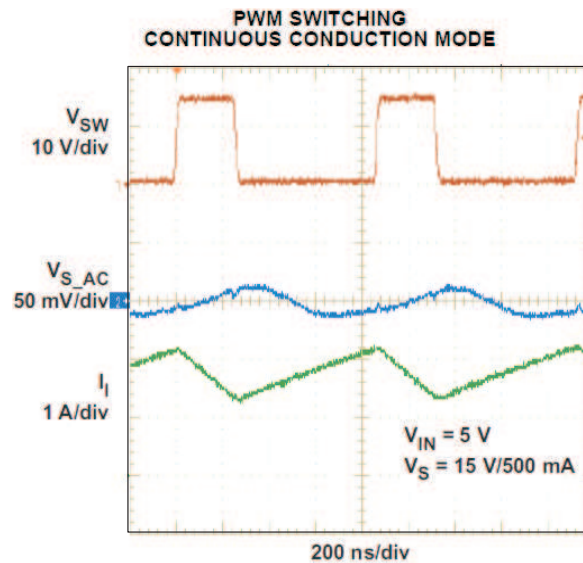

Figure 2. Continuous Step-up Converter Waveforms in Continuous Conduction Mode

Depending on the desired output voltage, a higher or lower duty cycle may likely be required. The duty cycle for the switch node can be found using Equation 1.

$$D = 1 - \frac{V_{IN\_Converter} \cdot \eta}{V_{OUT\_Converter}}$$

(1)

Where:

η = converter efficiency at a specified load

The duty cycle is important in the charge pump application because it places different charge times on the flying and storage capacitors. Additionally, the duty cycle increases with lower efficiency values.

2   Charge Pump Doubler Circuit

The switch node and output voltage of the boost converter generate an unregulated auxiliary positive output voltage that is roughly twice the main output voltage. An additional linear regulator or simple regulation transistor with a Zener diode can easily be added to the output of the charge pump for voltage regulation. Figure 3 illustrates the charge pump and the switch node of the boost converter.
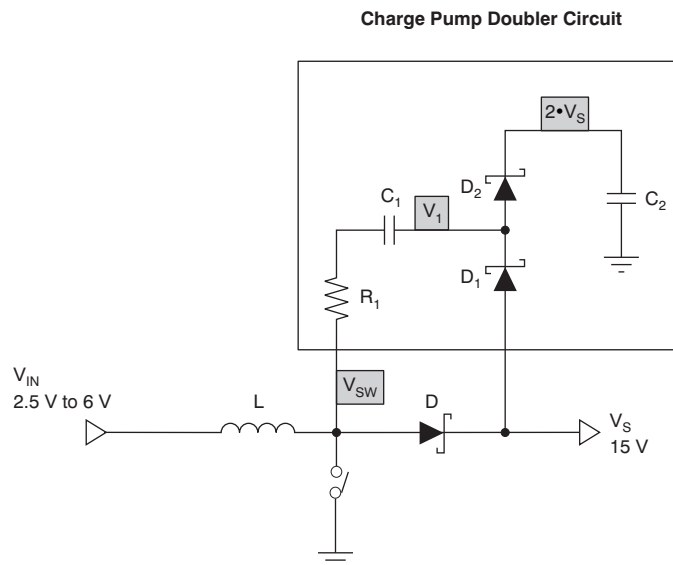
Charge Pump Doubler Circuit

Figure 3. Positive (2 × V$_S$) Charge Pump

During the device on-time, with $V_{SW} = 0$ V, the flying capacitor C_1 charges to $V_S - V_{D1}$ through the diode D_1. During the device off-time, the switch node voltage goes high to $V_S + V_D$, lifting C_1 (which is already charged with $V_S - V_{D1}$), by $V_S + V_D$ (the boost converter diode voltage drop). This action thereby charges the storage capacitor C_2 to:

2 $\bullet$ $V_S + V_D - V_{D1} - V_{D2} = 2V_S - V_D$

through the diode D_2 (assuming that $V_D = V_{D1} = V_{D2}$, and neglecting losses in the diodes, the capacitor C_1, and the current limiting resistor, R_1). Diode D_2 turns on only when the switch is off, so output capacitor C_2 must supply the required load current to the circuit during the device off-time.

3 Output Voltage Under Variable Load Conditions

The output voltage depends on the output load. The amount of drop can be found using the on- and off-time voltages on the capacitors.

During the on-time, with $V_{SW} = 0$ V, the flying capacitor C_1 is charged to the value expressed by Equation 2:

$$V_{C1} = V_S - V_{D1} - 2I_O(ESR_{C1} + r_{D1} + R_1)$$

(2)

Where:
- V_S = Output voltage of the boost converter
- V_{D1} = Voltage drop of diode D_1
- I_O = Output current of the charge pump
- r_{D1} = Resistance of diode D_1.
- ESR_{C1} = ESR of the flying capacitor, C_1.

During the off-time, the storage capacitor C_2 is now charged to V_{C1} in addition to the voltage at the switch node, V_{SW}. The output voltage can then be found as Equation 3:

$$V_{OUT} = V_{SW} + V_{C1} - V_{D2} - 2I_O(ESR_{C2} + r_{D2} + R_1)$$

(3)

Where:
- V_{SW} = Voltage on the switch node of the boost converter
- V_{C1} = Voltage across the flying capacitor C_1 (from Equation 2)
- V_{D2} = Voltage drop of diode D_2
- I_O = Output current of the charge pump
- r_{D2} = Resistance of diode D_2.
- ESR_{C2} = ESR of the storage capacitor, C_2.

These calculations give an equation for V_{OUT} as Equation 4 shows:

$$V_{OUT} = V_{SW} + V_S - V_{D1} - V_{D2} - 2I_O(ESR_{C1} + ESR_{C2}) - 2I_O(r_{D1} + r_{D2}) - 4I_OR_1$$

(4)

The charge pump output voltage can now be estimated under varying load conditions.

Figure 4 compares the calculated load regulation and measured load regulation as a function of the output current. The discrete charge pump doubler was built using a TPS61087 that switches at 1.2 MHz. $V_S = 15$ V for this design; $R_1 = 10\Omega$, and $C_1 = C_2 = 470$ nF. The diodes used in this application are the BAV99, which have a forward voltage drop of 1 V at 50 mA.
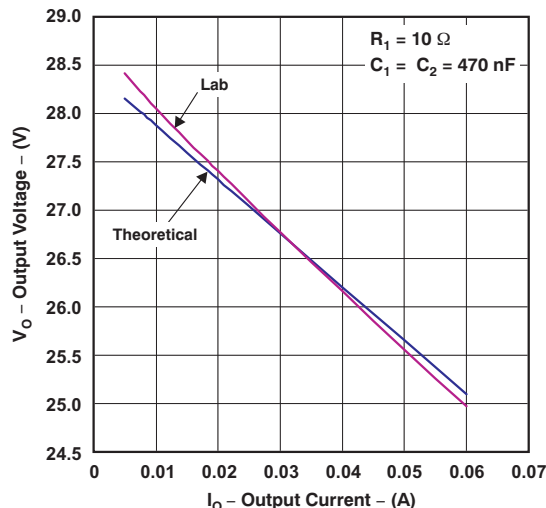

Figure 4. Estimated V_{OUT} Performance Under Varying Load Conditions vs Lab Results

4   Component Selection

4.1   Capacitor Selection

The flying capacitor is responsible for maintaining the voltage from the switch node. It should not be large enough in value [and therefore have higher equivalent series resistance (ESR)] that it could cause unnecessary dc losses because of the current flowing through it. At maximum output current, the ripple calculated on the flying capacitor should be between 100 mV to 500 mV to leave enough room for load transients. The ripple can be found using Equation 5:

$$V_{RIPPLE} = \left(\frac{I_{OUT} \bullet D}{C \bullet f} \right) + (I_{OUT} \bullet ESR_C)$$

(5)

Where:
- I_{OUT} = Output current of the charge pump
- D = Duty cycle of the boost converter
- C = Capacitor value
- f = Frequency of the boost converter
- ESR_C = ESR of the flying capacitor, C

The flying capacitor is selected based on the output current required and the ripple allowed. Typical ranges for the flying capacitor is 100 nF to 1 µF for most requirements; however, specific requirements may require larger or smaller flying capacitor values.

The value of the storage capacitor is chosen based on the maximum output current, the output voltage ripple allowed, and the load transient response. The output voltage ripple on the storage capacitor can also be calculated using Equation 5. The output voltage ripple results primarily from the charging and discharging of the storage capacitor as well as the ESR if the capacitance is large enough. Using a ceramic capacitor with X5R dielectric or better will help to reduce ripple from ESR. Additionally, if the application has a larger duty cycle, larger capacitor sizes are recommended because they help to reduce the ripple and hold the voltage constant. Typical ranges for the storage capacitor is 470 nF to 10 µF for most requirements. However, specific applications may require larger or smaller storage capacitor values. Additionally, to account for dc bias loss, both the flying and storage capacitors should be rated to withstand double the switch voltage.

4.2   Resistor Selection

The smaller value the flying capacitor has, the higher the current peak flowing through it. Placing a resistor before the flying capacitor helps to reduce the current spikes if the capacitor is not charged to its nominal value. This current must be limited because it can lower circuit efficiency and degrade the charge pump performance. However, the resistor value should not be too low (that is, less than 1 Ω) because it will then not sufficiently limit the current (as Figure 5a shows). Figure 5b shows the ideal current waveform through C_1 with a 100-Ω resistor. While higher resistor values sufficiently limit the current, the losses caused by this resistor are not negligible and can cause voltage drop on the output; see Equation 4. The value for this resistor completely depends on the output current. 10 Ω is an optimal value that limits the current without too much loss for most application requirements.

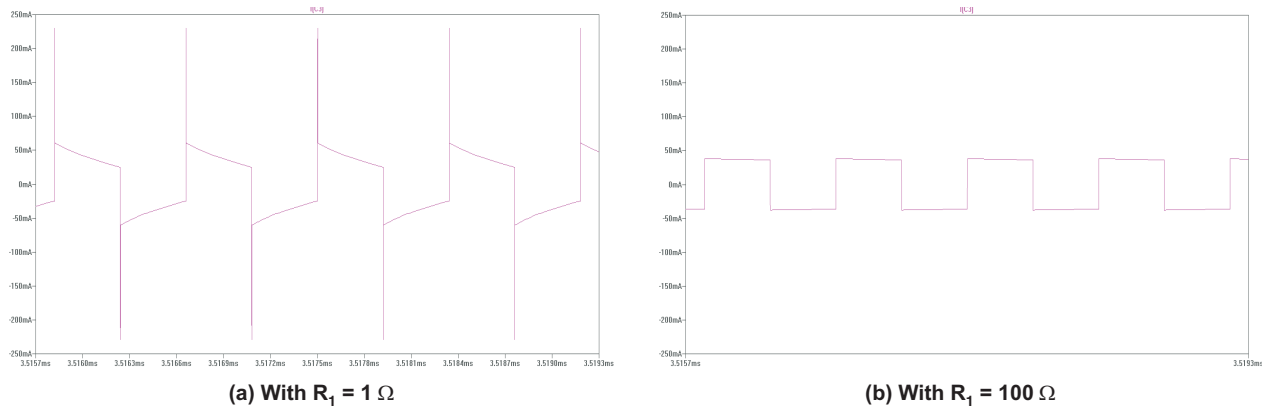Figure 5 shows how R_1 limits the current through C_1.

(a) With $R_1 = 1\ \Omega$ (b) With $R_1 = 100\ \Omega$

Figure 5. Flying Capacitor (C_1) Current

4.3 *Diode Selection*

The diode should be chosen to minimize forward voltage drop for higher efficiency. The reverse voltage rating should be higher than the maximum value of the voltage output of the boost converter. The forward current rating should be able to meet the load output and the peak current specifications.

5 Example

A common application that requires auxiliary voltage rails is a TFT-LCD display. For this example, +15 V at 500 mA and +25 V at 20 mA are required. The 15-V rail is supplied by the boost converter and the +25-V rail is supplied using a discrete charge pump circuit implemented with the TPS61087 together with a low-dropout regulator (LDO) for output regulation. (See Texas Instruments' application note SLVA119, *Extending the Input Voltage Range of an LDO Regulator* for more information on the LDO regulator.) The discrete charge pump will be designed for a minimum voltage drop. The maximum output voltage ripple allowed on the storage capacitor will be V_{RIPPLE} = 50 mV.

In this example, the TPS61087 has an output voltage of 15 V and a frequency of 1.2 MHz. The current-limiting resistor is set to R_1 =10 Ω and BAV99 diodes are used for D_1 and D_2. A maximum output voltage ripple of less than 50 mV is required for this application. Rearranging Equation 5, the output storage capacitor C_2 value can be calculated with Equation 6:

$$C_2 = \frac{20\text{ mA} \bullet 0.67}{50\text{ mV} \bullet 1.2\text{ MHz}} = 222\text{ nF}$$

(6)

An important factor to remember when calculating the storage capacitor is the effect of dc bias. A capacitor rated at 50 V that has a 30-V dc bias applied to it can lose 50% or more of its capacitance. Therefore, either the capacitor voltage rating or the capacitor value must be increased in order to meet the minimum capacitance requirement of the application. The cost differential for small-value capacitors is negligible; therefore, a 470-nF capacitor is chosen, which is double the recommended 222 nF minimum value.

The value of the flying capacitor is calculated using a minimum voltage ripple requirement for load transients. 250 mV is chosen for this example.

$$C_1 = \frac{20\text{ mA} \bullet 0.67}{250\text{ mV} \bullet 1.2\text{ MHz}} = 45\text{ nF}$$

(7)

Again, doubling the value to account for dc bias, the value chosen is 100 nF.

Rearranging Equation 4 and keeping the resistance of the diodes (r_D) and ESR of the capacitors negligible, the output of the charge pump at the desired load current can be found using Equation 8:

$$V_{OUT} = 15\text{ V} + 15\text{ V} - 0.9\text{ V} - 0.9\text{ V} - (4 \bullet 20\text{ mA} \bullet 10\ \Omega) = 27.4\text{ V}$$

(8)

Using C_1 = 100 nF and C_2 = 470 nF, the expected output voltage is 27.4 V at an output current of 20 mA. The ripple on the output should be less than 50 mV. Figure 6 shows the output voltage ripple and switch node under these conditions.
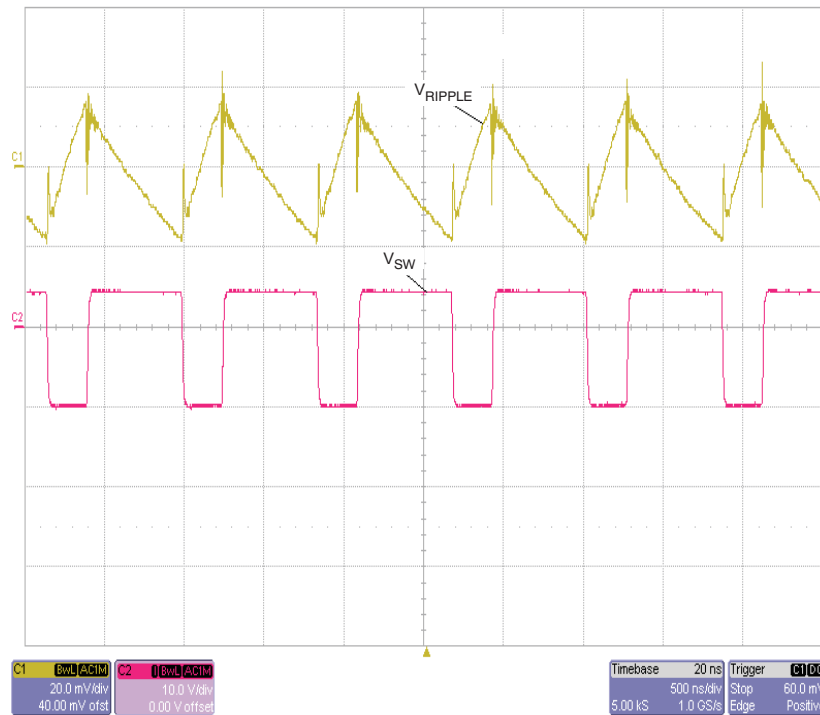

Figure 6. Output Voltage Ripple of 40 mV and Switching Voltage Across the Flying Capacitor

The output voltage was measured to be 27.45 V at a load current of 20 mA, which is close to the predicted value of 27.4 V. The LDO can then be used to regulate the voltage down to the required 25 V.

6   Conclusion

This application note demonstrates a simple circuit that can provide auxiliary voltages using the TPS61087 single step-up converter. The circuit can be implemented under a variety of voltage and load conditions.

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