Cypress MicroSystems

Application Note AN2097

Switch Mode Pump

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Associated Project: No
Associated Part Family: CY8C25xxx, CY8C26xxx

Summary

The PSoC[TM] device Switch Mode Pump (SMP) includes a boost converter and a voltage-controller loop that allows conversion of low voltage (e.g., battery) inputs to 3.3V and 5.0V operating levels.

Introduction

Many applications operate from a low voltage source, but still need a higher regulated voltage. The SMP is a boost converter with flyback topology that converts a low voltage to a higher voltage. The control loop allows regulation to the desired value.

This Application Note includes:

- A brief tutorial on boost-converter operation.
- Implementation of the SMP in PSoC Designer.
- Performance of the SMP for 3.3V and 5V applications.
- Board layout techniques.

Boost Converter Operation

The boost converter, shown in Figure 1, uses a switching device to transfer power from a battery through an inductor as an energy storage device to the filter capacitor and load:

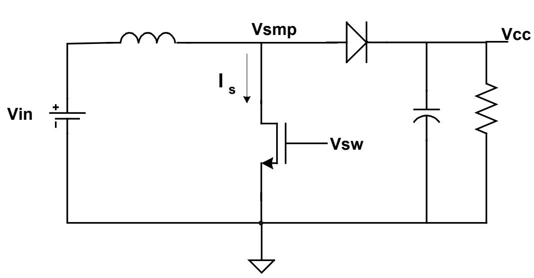


Figure 1: Boost Converter Circuit

When the switch is closed (storage phase), the input voltage is applied to the inductor. The inductor current (I_{in}) increases linearly as shown in Equation (1):

$$I_{in}(t) = \frac{V \cdot t_1}{L} \qquad (1)$$

The diode prevents the filter capacitor from discharging into the switch, Q1. The energy stored in the inductor while the storage phase is given by:

$$E = \frac{1}{2} L I_{in}^2 \qquad (2)$$

When the switch is opened, the inductor current continues to flow; this causes the voltage at node V_{smp} to "flyback" to a voltage higher than the capacitor voltage. This triggers the diode to start conducting which in turn allows the charge stored in the inductor to be transferred into the filter capacitor. Equation (3) shows the transfer of power in the boost converter:

$$\frac{1}{2} C V_{new}^2 = \frac{1}{2} L I_{in}^2 + \frac{1}{2} C V_{old}^2 \qquad (3)$$

Voltage and current waveforms for the standard form of the boost converter are shown in Figure 2:

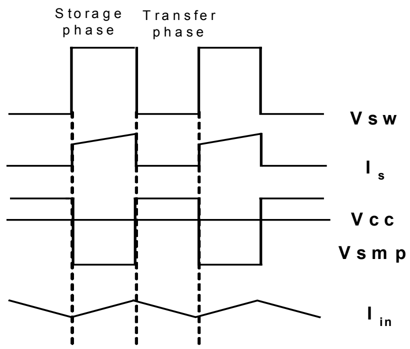


Figure 2: Voltage and Current Waveforms in a Boost Converter

Unless the output voltage V_{cc} is controlled, this boosting will go on indefinitely until something breaks. A feedback circuit switches off the oscillator driving the switching transistor to implement this control.

PSoC Implementation

The PSoC implementation of the Switch Mode Pump is shown in Figure 4. In the PSoC device, the voltage control loop compares the voltage V_{cc} with the SMP trip voltage. The SMP trip voltage can be set either in the "Trip Voltage [LVD (SMP)]" entry of Global Resources in the Device Editor or by setting the VM [2:0] bits in the Voltage Monitor Control Register (VLT_CR) in the user's code. The SMP must be enabled either in the Device Editor or by writing 1 to the SMP bit (bit 7) of the VLT_CR.

SwitchModePump	ON
Trip Voltage [LVD (SMP)]	4.64V (5.00V)
Supply Voltage	5.0V

Figure 3: Global Resource Settings

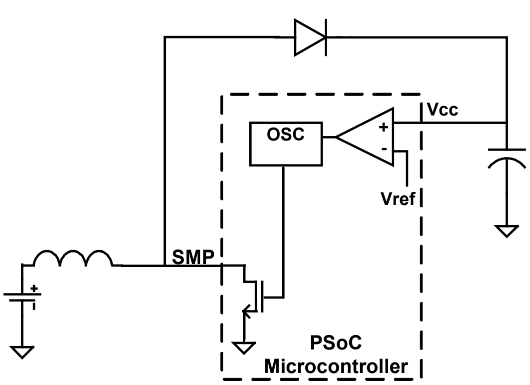


Figure 4: SMP using Feedback Loop in PSoC

The monitor compares the V_{cc} voltage with the SMP trip voltage. When the trip voltage (V_{ref}) is larger than the V_{cc}, the comparator enables the oscillator. The oscillator generates a pulse to turn on and off the switch. The oscillator runs at a nominal frequency of 1.3 MHz.

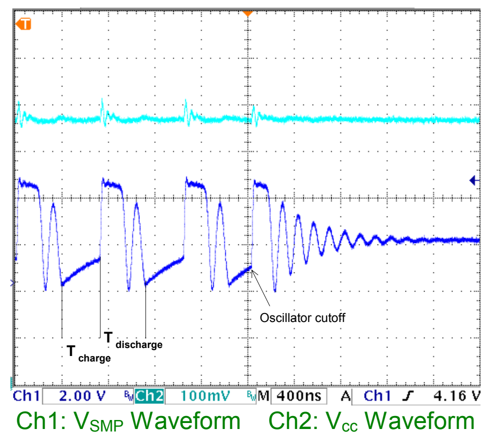


Figure 5: Output Voltage Ripple and SMP Voltage

Figure 5 shows the output voltage (V_{cc}) and the waveform at the SMP node (V_{SMP}). The choice of capacitor at the V_{cc} node determines the ripple at the output voltage. The voltage at SMP node shows the switching operation clearly. When the voltage at V_{cc} drops below the set value (V_{REF}), the oscillator turns on and switching starts. The period for which the switch is turned on corresponds to the charge phase shown in Figure 4. The voltage during charge phase ramps up due to the presence of the resistances in the circuit. Then, the switch is turned off (discharge phase) and V_{SMP} flies up to a value greater than the output voltage V_{cc} plus the drop across the diode. When all of the energy in the inductor is dumped, the inductor voltage will ring. Once the voltage across the capacitor reaches the set value of V_{cc}, the oscillator and the SMP voltage remain constant.

Design Details

The parameters of interest in a SMP are the maximum load current that can be delivered and the efficiency. Resistances in the circuit limits the inductor current and changes Equation (1) to:

$$I_{in} = \frac{V_{in}}{R_t}\left(1 - e^{-t/\tau}\right) \quad (4)$$

where,

t = on time of the switch

$\tau = \frac{L}{R_t}$ is the time constant of the circuit and

$$R_t = R_{sw} + R_{ind} \qquad (5)$$

Where:
R_{sw} = 8 Ω, the switch resistance.
R_{ind} = Inductor DC resistance.

The power in the inductor during the storage or charging phase is:

$$P_{charge} = \frac{1}{2} L I_{in}^2 f \qquad (6)$$

where *f* is the frequency of the oscillator.

Discharge time or transfer time is:

$$t_{discharge} = \frac{I_{in} L}{(V_{out} + V_{diode} - V_{in})} \qquad (7)$$

The power delivered during discharge is:

$$P_{discharge} = \frac{1}{2} I_{in} f V_{in} t_{discharge} \qquad (8)$$

Total power $P_{total} = P_{discharge} + P_{charge}$ (9)

The output current I_{out} is:

$$I_{out} = \frac{P_{total}}{V_{out} + V_{diode}} \qquad (10)$$

The efficiency is the ratio of power at the output to the total power delivered by the battery given as:

$$\eta = \frac{V_{out} I_{out}}{(0.25 V_{in} I_{in} + P_{discharge})} \qquad (11)$$

The switch resistance and the inductor resistance limit the efficiency of the SMP because the major component of power loss is the I^2R loss. Care must to taken to keep this resistance to a minimum. Since the switch resistance is not accessible, one of the critical parameters in choosing the inductor is the DC resistance. The DC saturation current of the inductor should be chosen to be greater than the peak inductor current.

The output capacitor can cause significant ripple due to its Equivalent Series Resistance (ESR). If aluminum capacitors are chosen to reduce cost, a ceramic capacitor should also be connected in parallel in order to minimize ripple. The hold time of the output voltage is shown in Figure 5 as the oscillator cutoff period. This is determined by the size of the capacitor used.

Schottky diodes are recommended because they have a low forward voltage and fast switching speed. The current rating of the diode should be greater than twice the peak load current. The breakdown voltage should be greater than V_{cc}.

Applications

3.3V Operation

Output voltage of 3.3V can be obtained using a nominal 1.5V single-cell battery. Using a capacitor of 0.1µF, a Schottky diode of 1A current rating, inductors of current rating more than 300 mA, and DC resistance less than 0.5 Ω, the SMP starts regulating the output voltage to within 5% of the set value at an input voltage of 1V. But as the load is increased, the required minimum voltage to maintain regulated output also goes up.

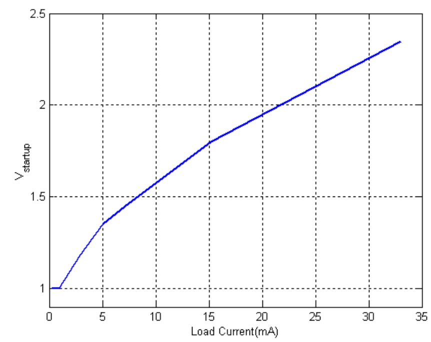
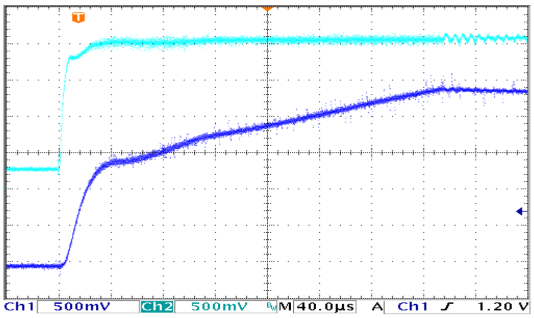


Figure 6: Startup Voltage vs. Load Current

The start-up time of the SMP, defined as the time taken for the output voltage to reach 5% of the set SMP trip voltage, is less than 1 ms with no load connected (Figure 7). The output voltage increases quickly until it reaches the input value and then slopes up to the set output value due to the pumping action.



Ch1: V_{cc} Ch2: V_{batt}

Figure 7: Start-up Time of the SMP with No Load

Note that the inductor current (Figure 8) decreases as the inductor value is increased. This can be seen from Equation (5). The input current is so high because it is a function of the efficiency obtained, the battery voltage, the output voltage, and the load current as can be readily seen from Equation (11).

$$I_{in\_average} = \frac{I_{out} \cdot V_{out}}{V_{in} \cdot \eta} \quad (12)$$

Typically, input currents are larger than the output current as shown in Equation (12). For example, to drive a load of 10 mA at 3.3V with a 1.3V battery and get 3.3V V_{cc} with an efficiency of about 80%, the input current drawn is about 30 mA.

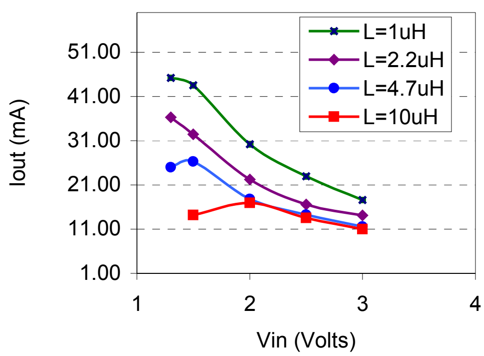


Figure 8: Inductor Current vs. Input Voltage with a Load of 5 mA

The efficiency of the SMP for 3.3V operation increases with inductor value. This is because as the inductor value increases, the input peak current decreases. This makes the I^2R loss incurred lower, thereby increasing the efficiency of the system (Figure 9). The efficiency does not depend on the load on the system. As the load to be driven increases, the system draws a larger current from the battery by increasing the operating duty cycle of the oscillator.

Figures 9 and 10 show typical values for efficiency and maximum-load current that the SMP can drive. Appendix A gives worst-case values of efficiency and load currents that the SMP can drive from a sampling of parts.

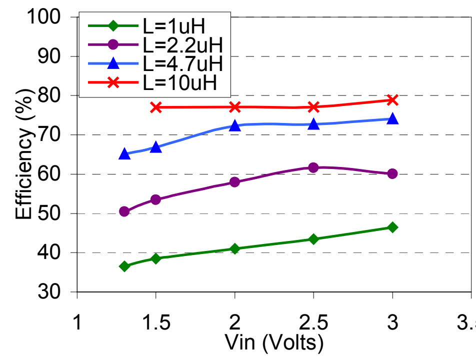


Figure 9: Typical Efficiency Values at Room Temperature

The maximum-load current that can be driven by the SMP is a function of the input battery voltage and the inductor used, as shown in Figure 10. The output current delivered increases as the inductor value is increased for larger battery voltage. This is because the inductor current I_{in} is inversely proportional to the inductance value, thereby reducing the I^2R loss and increasing the power delivered. Greater output power delivered equates to larger load that can be driven.

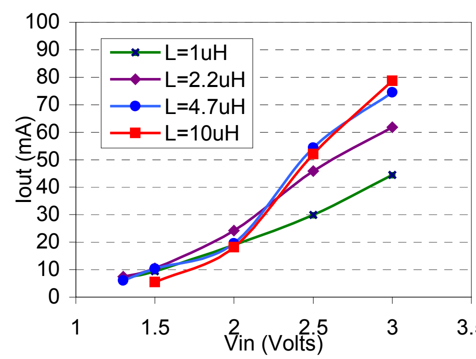


Figure 10: Typical Values of Maximum Load Current

Therefore, to choose the inductor value that works best for your application, look at the maximum output current graph (Figure 10) first to see what inductor range will be needed to drive the desired load. Then, looking at Figure 9, the efficiency of the system while using a particular inductor can be determined.

Figure 11 shows how efficiency varies with temperature. The efficiency of the system is higher at cold temperatures because the losses due to the on-resistance of the FET are lowered at low temperatures.

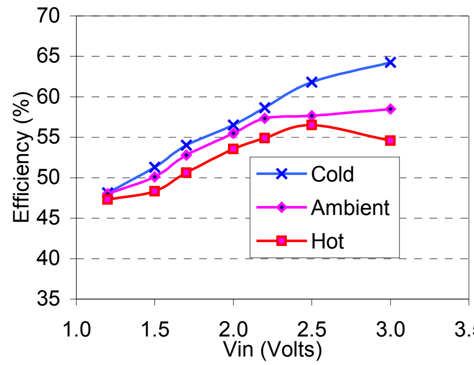


Figure 11: Typical Efficiency Curves at Different Temperatures for a 2.2 µH Inductor

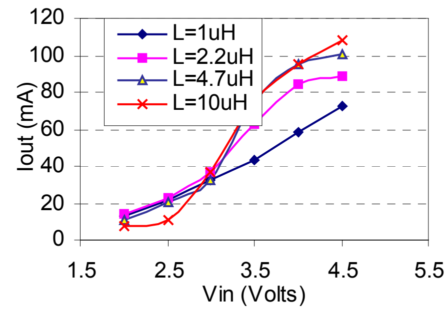


Figure 13: Typical Values of Maximum Load Current

All the above data were obtained using a 10 µF output capacitor. A Schottky diode of 1A current rating and a 10 µF bypass capacitor at the battery input and inductor DC resistances less than 0.5 Ω were also used.

5V Operation

Figure 12 shows typical efficiency values obtained with a multi-cell input to get a V_{cc} of 5V. Comparing this with Figure 8, it can be seen that using the SMP for 5V operation has more or less the same efficiency as 3.3V operation. Minimum values of efficiency for 5V operation are shown in Appendix A.

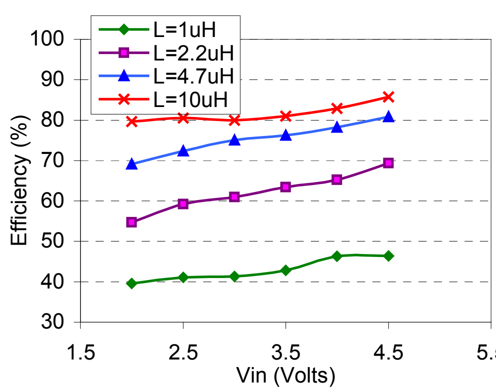


Figure 12: Typical Efficiency Values

Note that a larger load can be driven for low voltages with 3.3V operation as compared to 5V operation. Whereas the battery voltage is increased, the 3.3V operation can drive larger load current. Appendix A gives worst-case load current that can be driven using various inductors.

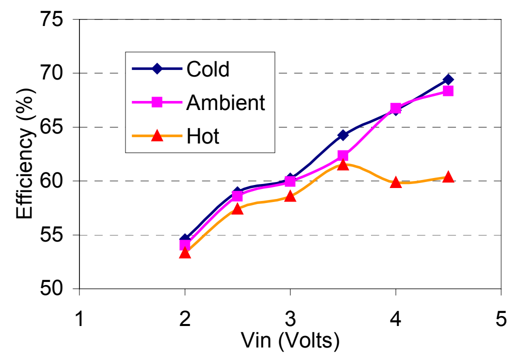


Figure 14: Typical Efficiency Curves at Different Temperatures

For a 5V operation, efficiency shows the same behavior with temperature as a 3.3V operation.

Since it's a power-supply board, one must be careful to use short traces so as to avoid parasitic inductances. A clean ground is essential to get the best performance. If the battery is connected through long leads, it adds inductance to the circuit, thereby behaving like a higher inductor. Connecting a sufficiently big capacitor at the input node will negate this effect.

Conclusion

The methodology for building a Switch Mode Pump using the PSoC device has been shown here with three external components and the performance documented.

Appendix A

See the following minimum values of efficiency and maximum output current for both 3.3V and 5V operation obtained from a sampling of parts:

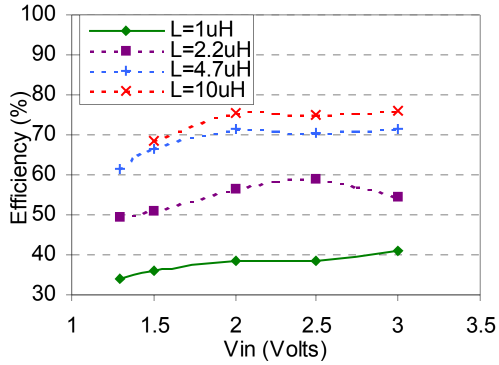


Figure A1: Minimum Values of Efficiency for 3.3V Operation

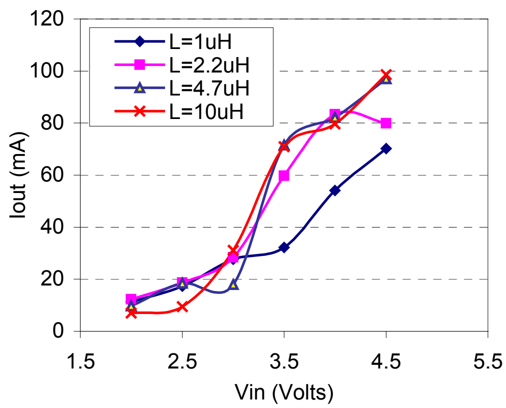


Figure A2: Minimum Values of Maximum Load Current for 3.3V Operation

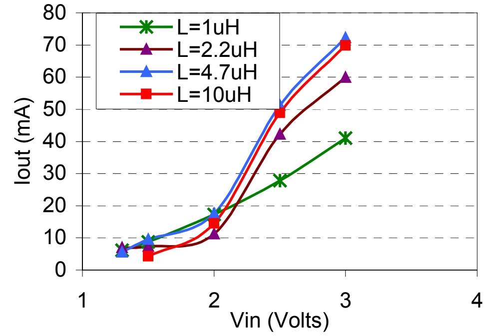


Figure A3: Minimum Values of maximum load current for 3.3V Operation

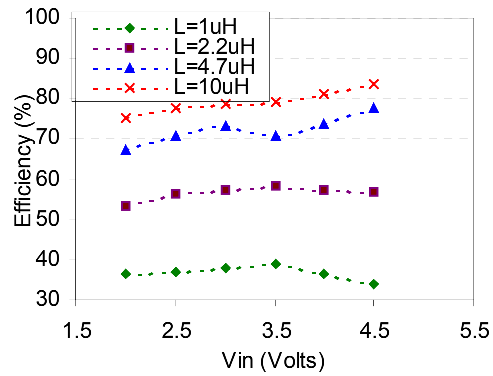


Figure A4: Minimum Values of Efficiency for 5V Operation

Appendix B

Part numbers used to obtain the above data are:

Schottky Diode Through Hole
1A, 20V Micro commercial components - 1N5817
Future Active – MCCN2381

Inductors Surface Mount
1uH – Panasonic - ELJ-EA1R0MF
Digikey - PCD1417CT-ND
2.2uH – Panasonic - ELJ-EA2R2MF
Digikey - PCD1419CT-ND
4uH – Panasonic - ELJ-PA4R7MF
Digikey - PCD14CT-ND
10uH – Panasonic - ELJ-PA100KF
Digikey - PCD1484ct-ND

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