SYNCHRONOUS CONVERTER TO BOOST BATTERY VOLTAGE

Disposable alkaline batteries are used in many portable devices because of their low cost and their availability. Although not typically exploited by the device power converter, a single-cell alkaline battery has useful capacity from 1.6 V down to below 1 V. By extending the input voltage range of the converter to operate over the usable voltage range of the cell, the runtime of the portable device can be increased significantly. The boost converter presented in this article will start up and deliver full rated current with a 1 V input and operate down to 0.4 V. Maximum battery utilization is realized by integrating low on-resistance switches, synchronous rectification, and an adaptive current mode control scheme. The converter develops multiple output voltages from a single inductor using a multiplexing technique.

BACKGROUND

The rapid growth of portable equipment has been fueled by strong customer demand that has resulted from significant advances in digital and radio frequency (RF) technologies. Features such as e-mail, global positioning systems (GPS), and two-way communications are making handheld portable instruments more versatile, while many of these new features increase the power demands on the battery. Although battery performance is improving with the introduction of new chemistries, it has not kept pace with the increased functionality found in today's portable equipment. Switch mode power conversion can offer efficiency improvements when compared to linear techniques, increasing battery utilization. Unique challenges exist, however, in implementing a switch mode solution for a battery-powered system. Portable devices have a wide dynamic load range that can vary from a few milliwatts to hundreds of milliwatts. Many portable devices require the converter to operate off the voltage of a single cell, which, depending on the power level of the application, can pose a significant challenge.

DISPOSABLE ALKALINE CELL PERFORMANCE

Alkaline is the disposable battery of choice for portable devices because of a low self discharge (about 5% a year) and a high energy density. For many applications, such as two-way pagers, the average load on the alkaline battery is low but the peak load can be over 500 mW. This can equate to peak currents of more than 500 mA from a single cell. Figure 1 shows the voltage of an AA battery discharged at 500 mA. Open circuit voltage was measured by removing the load for 10 s each minute.

Battery equivalent series resistance (ESR) is shown in Fig. 1 to have a large influence on the actual voltage measured at the terminals. A battery with 1.1 V at no load, for example, will drop to 0.9 V with a 500 mA load. The power conversion circuitry will need to handle the low-voltage droop during these peak power durations. This can often be the limiting factor in the ability to deliver sufficient output power to the application.

ACHIEVING HIGH EFFICIENCY OVER A WIDE DYNAMIC RANGE

The battery's energy capacity and the converter's efficiency will determine the available run-time of the device. Portable equipment may require hundreds of milliamps when the device is fully functioning. In standby mode, where the device spends a majority of time, the equipment may require less than 1 mA. The amount of time the device spends in various modes is heavily dependent upon the user. Because it is difficult to predict how the device will be used, it is important that the converter operates efficiently over a wide dynamic load range.

Discontinuous Mode Efficiency

An analysis of the converter losses can provide insight into determining a control scheme that will operate efficiently. Figure 2 shows a low-voltage synchronous boost converter along with the equivalent circuit elements that are major contributors to power loss. Switch capacitance has been reflected to the gate for simplicity.

To support a wide dynamic load range with a reasonably small value of inductance, the boost converter must operate in discontinuous conduction mode at medium and light loads.

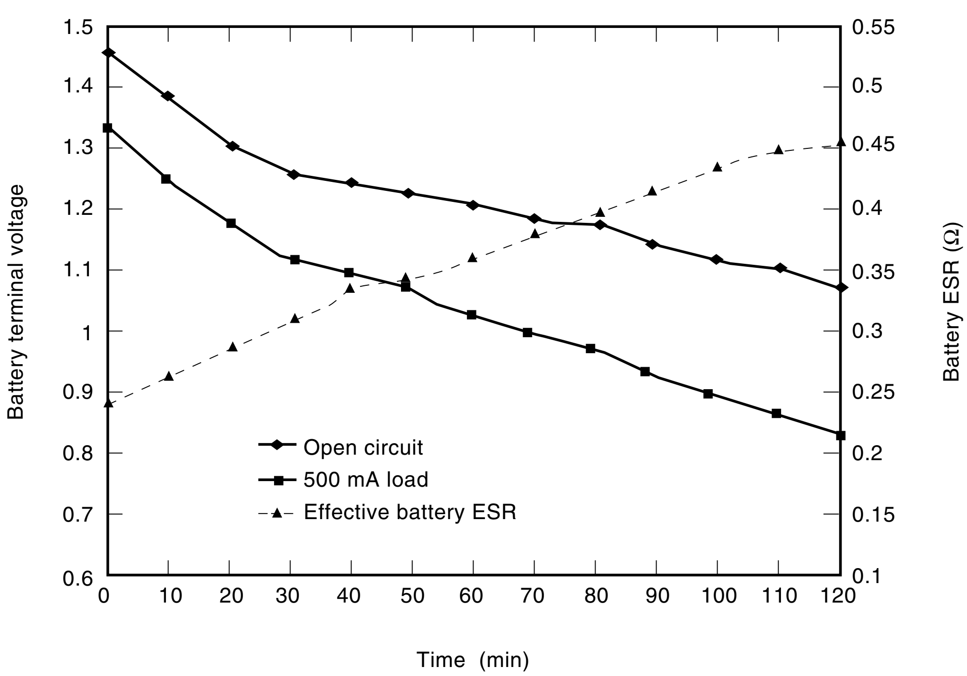


Figure 1. AA alkaline battery voltage at a 500 mA discharge rate.

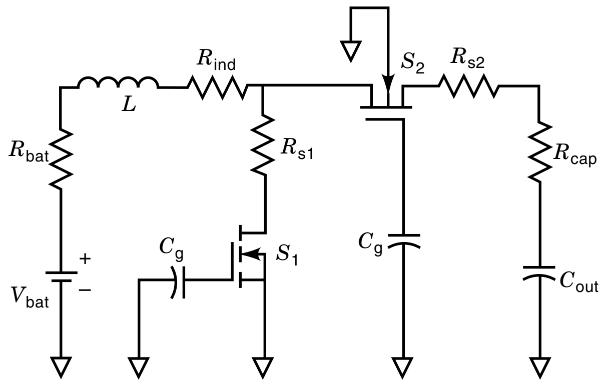


Figure 2. Synchronous boost converter and equivalent circuit elements.

Table 1. Input and Lost Energy for a Single Conversion Cycle in Discontinuous Conduction Mode

Input energy	$E_{in} = \frac{1}{2} \cdot I_{peak} \cdot V_{bat}\,(T_{ch} + T_{bst})$
Conduction energy lost	$E_{cond} = \frac{I_{peak}^2}{3}(R_{ch}T_{ch}R_{bst}T_{bst})$
Where	$R_{ch} = R_{bat} + R_{ind} + R_{s_1}$ $R_{bst} = R_{bat} + R_{ind} + R_{s_2} + R_{cap}$
Switching energy lost	$E_{sv} = 2 \cdot C_g \cdot V_g^2$
Control chip quiescent current (I_{DD}) energy lost	$E_{I_{DD}} = V_{DD} \cdot I_{DD} \cdot T_{cyc}$
Resulting efficiency (%)	$\text{Efficiency} = 100 \cdot \left[1 - \frac{(E_{cond} + E_{sw} + E_{I_{DD}})}{E_{in}}\right]$

Figure 3 shows inductor current in discontinuous conduction mode.

Discontinuous mode efficiency can be calculated from the input and loss energy for a single conversion cycle. Based of Figs. 2 and 3, Table 1 gives approximate energy values and the resulting overall efficiency.

These equations can now be used to determine the optimum peak inductor current for the converter in discontinuous conduction mode. Figure 4 shows the losses and overall efficiency versus peak current of an integrated boost converter with a 1.5 V input and a 3.3 V, 5 mA output.

As shown in Fig. 4, conduction losses dominate with large peak currents, where switching losses dominate with small peak currents. The optimum peak current in this case is around 250 mA. It is interesting to note that if the load current is increased to 20 mA, or decreased to 1 mA, the optimum peak current is still 250 mA. In fact, in discontinuous conduction mode, the optimum peak inductor current is independent of load current.

The reason this occurs can be seen by looking at the equations in Table 1 that detail the energy of a single conversion cycle. Input energy is related to peak current and, for a given value of peak current, is fixed with no dependence on the load current. The conduction energy lost during a single conversion cycle is also fixed for a given peak current regardless of the load. The switching energy lost is only related to gate capacitance and gate drive voltage. The I_{DD} energy lost during a single conversion cycle is affected by the conversion period T_{cyc}, which is a function of load current. As T_{cyc} increases at light loads, the I_{DD} energy lost will also increase, thereby reducing efficiency. I_{DD} losses ($E_{I_{DD}}/E_{in}$) show up as an offset in efficiency however (see Fig. 4), which means that I_{DD} will change the efficiency with respect to load current, but not to the optimal peak current.

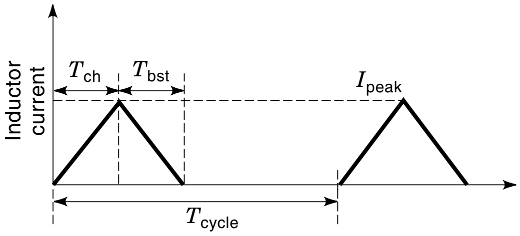


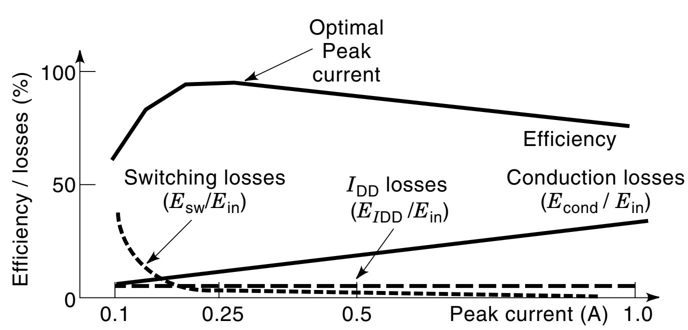
Figure 3. Discontinuous mode inductor current.

Because discontinuous mode efficiency (for a given converter) is optimized at only one peak current, a control technique that maintains a constant peak current should be selected. With a fixed frequency control technique, the amount of energy delivered to the load is adjusted by keeping the cycle time fixed and by controlling the peak current in the inductor. Because peak current is varied, this technique does not offer good efficiency over a wide dynamic load range. With pulsed frequency modulation (PFM), the cycle time, rather than the peak current, is adjusted to accommodate load variations. This allows an optimal peak current that will maximize efficiency in discontinuous conduction mode to be chosen.

Synchronous Boost Converter Description

The UCC3941 is a 500 mW boost converter that incorporates a PFM control technique. The part is available in three versions, depending on the voltage of the main output: 3.3 V, 5 V, or adjustable. Figure 5 shows a simplified block diagram of the UCC3941's internal control circuitry along with a typical applications circuit.

All necessary control circuitry is integrated into an eight-pin chip along with synchronous MOSFET switches. Few ex-



V_{in} = 1.5 V, V_{out} = 3.3 V, I_{out} = 5 mA, V_{dd} = 8 V, I_{DD} = 20 μA, C_g = 400 pF, L = 22μ H, R_{ch} = 0.55, R_{bst} = 0.75

Figure 4. Boost converter efficiency vs. peak current for a 5 mA output.

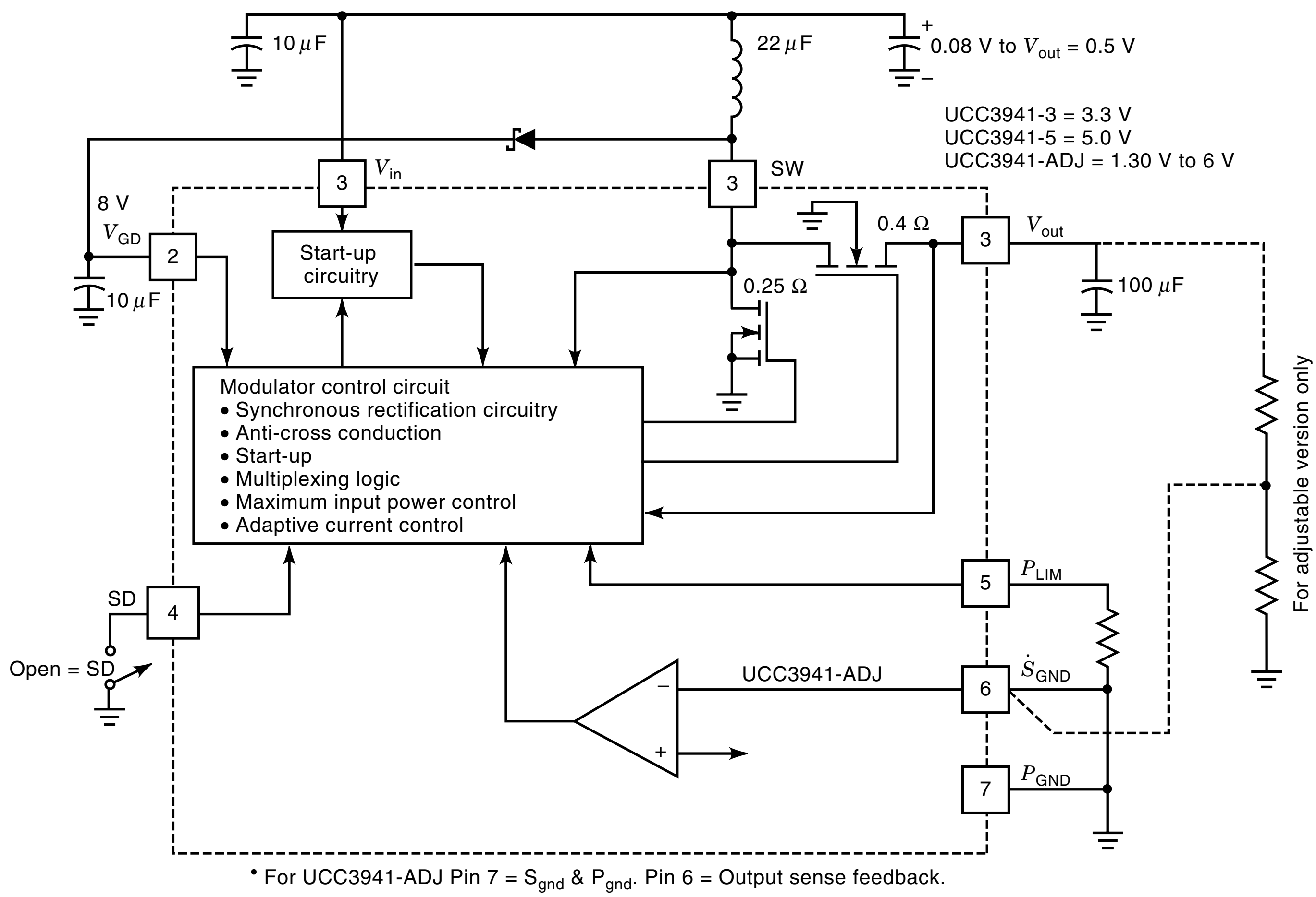


Figure 5. UCC3941 Simplified block diagram and application circuit.

ternal components are required, minimizing the board area for the converter. Low quiescent currents are achieved by turning off sections of control circuitry during periods of inactivity. Conduction losses are minimized through the use of low R_{DSON} switches. Equation (1) describes the relationships that determine the R_{DSON} for a MOSFET.

$$R_{DSON} = \frac{1}{\left[uC_{ox} \cdot \frac{W}{L_{eff}} \cdot (V_{GS} - V_T)\right]} \tag{1}$$

R_{DSON} is inversely proportional to gate drive voltage (V_{GS}) minus the threshold voltage (V_T = 0.7 V). Other parameters in the equation are fixed for a given switch geometry and silicon process. By generating an 8 V supply (V_{GS}) for the gate drive rather than using the main output voltage V_{out}, conduction losses are lowered by a factor of 2 to 3. Using 8 V achieves the best overall efficiency compromise between switching and conduction losses for the converter. The 8 V output can be used to support an additional 10 mA of load current for applications requiring an auxiliary output. By lowering conduction losses, the converter can deliver more current to the load at low battery voltages.

Figure 6 shows the output current capabilities of several low power boost converters with integrated MOSFETs. As the graph indicates, the load current capability of most converters decreases significantly at low battery voltages. Converter 1 operates in discontinuous conduction mode and has limited current capabilities. Converters 2 and 3 increase their output current capabilities with continuous mode operation, but their ability decreases at low input voltages. The UCC3941

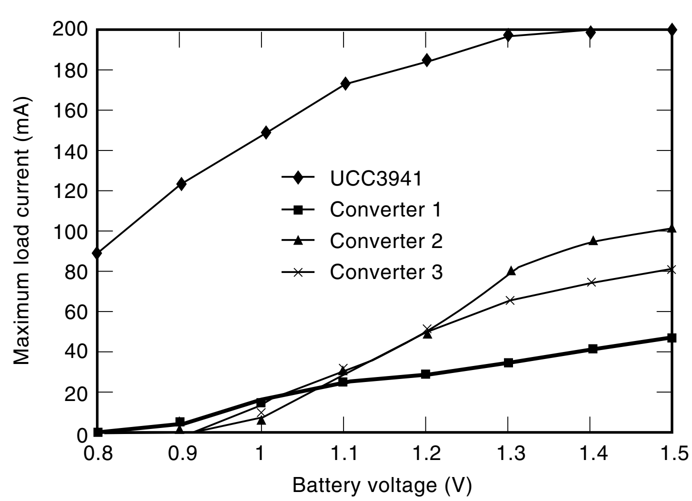


Figure 6. Output current capabilities of boost converters with 3.3 V outputs.

achieves improved capability by combining low R_{DSON} switches with continuous mode operation.

Continuous Mode Operation

Discontinuous conduction mode results in a simple control scheme; however, the average load current (reflected to the input) is limited to less than half the peak current. If the peak inductor current is increased, efficiency and the output voltage ripple will suffer. In order to provide increased load current, the UCC3941 is allowed to transition into continuous conduction mode (see Fig. 7). In order to keep the control scheme simple, while providing the ability to generate multiple outputs, a pseudo continuous conduction mode is implemented.

Referring to Fig. 7, if a single discontinuous mode energy pulse is not sufficient to bring the main output into regulation, the current in the inductor is allowed to increase until a maximum current I_{max} is reached. The I_{max} level is programmable for the load requirements of the device so that conduction losses can be minimized. The best continuous mode efficiency is achieved when I_{max} is set just high enough to provide for the peak load current of the particular application. To maintain constant input power capability, I_{max} is automatically varied when battery voltage decreases as follows:

$$I_{max} \propto \frac{1}{V_{bat}} \tag{2}$$

By using a hysteretic control technique, the stability problem of crossing the continuous/discontinuous mode boundary has been eliminated. A detailed description of how the converter transitions between modes and controls the current in the inductor is given in the section entitled [Multiplexed Waveforms.]

Efficiency Curves

Continuous conduction mode allows increased output power, whereas discontinuous PFM mode delivers optimal efficiency at light loads. The modes of operation are controlled with an internal state machine that adjusts charge times and current limits. By providing efficient conversion over the usable battery voltage in both modes, operation time is maximized. Figure 8 shows UCC3941 efficiencies over a 200 : 1 load range.

The upper curve is typical of a Lithium-Ion input and a 5 V output. The lower curve is typical of a single-cell alkaline input and a 3.3 V output. The converter can deliver 200 mA to the load, while maintaining good efficiency down to 1 mA.

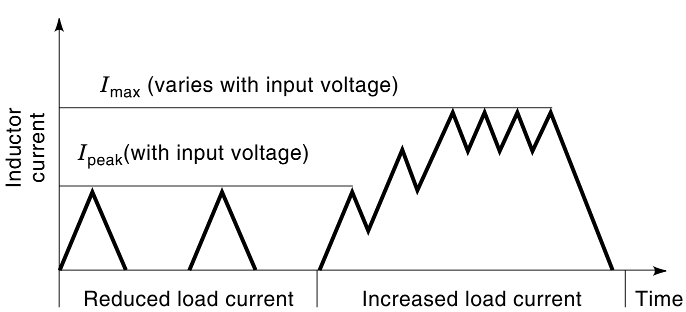


Figure 7. Adaptive current mode control.

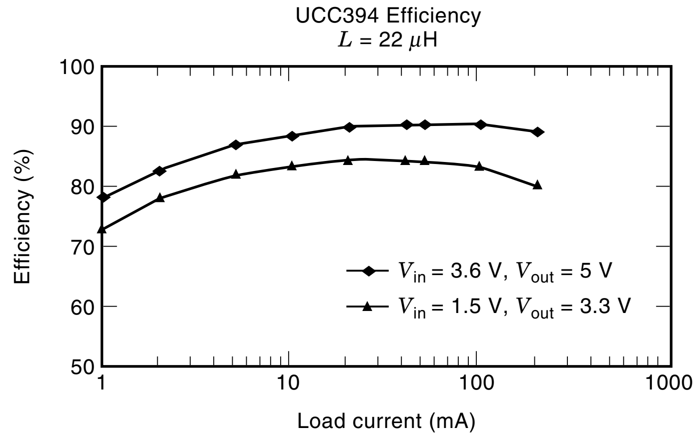


Figure 8. Efficiency as a function of load current and input and output voltage.

GENERATING MULTIPLE OUTLETS

In many portable applications, multiple output voltages are required. The additional voltage may be needed to drive an LCD display, interface logic circuits with a higher voltage driver, provide bias voltage for op-amp circuits, or generate a trickle charger for a backup battery. The design challenge is to provide additional outputs without increasing board real estate or compromising efficiency.

Traditional Choices

When multiple output voltages are required from a switching regulator, the circuit designer has traditionally been limited to a small number of topology choices. A multitap transformer solution in a forward or flyback configuration can provide multiple positive or negative outputs. This solution generally requires custom magnetics with the associated design, cost, and purchasing headaches. Typically, a single output is chosen for regulation, whereas the remaining outputs will have some level of cross-regulation dependent upon the loading. If more accurate regulation is required, a magnetic amplifier or post regulator can be used, but the additional board real estate and cost are usually prohibitive for portable applications. A linear regulator is generally employed if regulation on the secondary outputs is required.

At low power levels, charge pump circuits are often used to generate additional output voltages. Voltage doublers and triplers, as well as voltage inverters, can be implemented with inexpensive diodes and capacitors. Designed with discrete components, parts count can escalate with only a few additional outputs. Efficiency is generally compromised with this technique because of the presence of large currents during the charge transfer process. If the output voltage is not an integer multiple of the source voltage, some sort of regulation is needed to bring the charge pumped voltage to a desired value. Integrated charge pump solutions exist where the voltage is regulated and the charge current is controlled, thereby improving efficiency; however, a separate integrated circuit (IC) is generally required.

Multiplexed Coil Technique

The UCC3941 incorporates a unique multiplexed coil technique to generate multiple outputs from a single inductor. En-

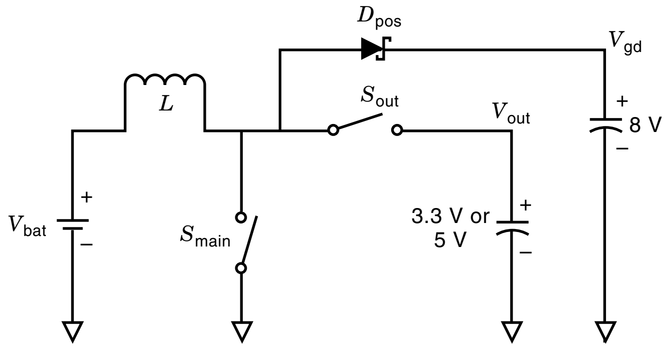


Figure 9. UCC3941 topology.

ergy pulses stored in the inductor are time shared between the outputs depending upon loading. Figure 9 shows a simplified schematic of the basic topology.

When either output requires service, S_{main} turns on and current ramps up in the inductor to the discontinuous or continuous peak value. The chip then determines which output will be charged. When V_{out} is charged, S_{out} is closed at the instant S_{main} is opened. When V_{gd} is charged, current is forced through D_{pos} when S_{main} is opened. Because of the presence of large peak currents in the inductor, low ESR capacitors should be used to maintain low ripple voltages on the outputs.

Arbitration

A priority scheme is required to accommodate multiple supply voltages, while providing effective start-up and servicing of the outputs at various load conditions. The arbitration rules for the 3.3 V version are as follows:

- If $V_{gd} < 7.6$ V, V_{gd} will get priority for service (start-up)
- If $V_{gd} > 7.6$ V and $V_{out} < 3.3$ V, V_{out} will get priority for service.
- If $V_{gd} < 8.7$ V and $V_{out} > 3.3$ V, V_{gd} will get priority for service.

In order to guarantee an orderly start-up with input voltages below 1V, the gate drive supply V_{gd} is given priority during start-up. Figure 10 shows oscilloscope waveforms of current and voltage during startup.

At time t_0, an internal 200 kHz oscillator toggles the main switch at 50% duty cycle, and V_{gd} starts to rise. V_{gd} gets to a sufficient voltage at time t_1 to run the IC in a normal mode. At time t_2, V_{gd} has reached its lower threshold of 7.6 V and the arbitration allows V_{out} to get started. V_{out} has reached 3.3 V at time t_3, and V_{gd} is allowed to charge to 8.7 V. At time t_4, both outputs are in regulation, and the converter operates normally, servicing the outputs as the load demands.

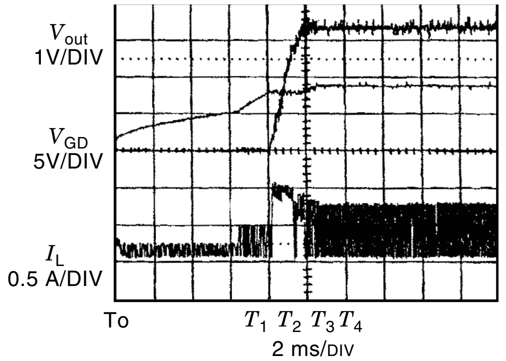


Figure 10. Start-up waveforms.

Multiplexed Waveforms

The UCC3941 converter develops a hysteretic control technique by monitoring the output voltages with comparators. If an output falls below its voltage threshold, the converter will deliver a single or multiple energy pulses to the output until the output comes into regulation. The inductor charge time is controlled by: $T_{on} = 12\ \mu s/V_{in}$. In discontinuous conduction mode, this results in a constant peak current, regardless of the input voltage. For a 22 μH inductor, the resulting peak current is approximately 500 mA. The on time control is maintained, unless the inductor current reaches the I_{max} limit. The inductor discharge time is fixed at $T_{off} = 1.7\ \mu s$, unless the output rises above its voltage threshold. The short off time allows the inductor current to transition to the I_{max} limit if a single pulse is not adequate. If the output voltage is satisfied after the 1.7 μs off time, the charge switch will not be activated, and the inductor current will decay to zero.

Figure 11 depicts typical voltage and current waveforms of the converter servicing two outputs. At time t_1, V_{out} drops below its lower threshold, and the inductor is charged for 12 μs/V_{in}. At time t_2, the inductor begins to discharge with a minimum off time of 1.7 μs. Under lightly loaded conditions, the amount of energy delivered in this single pulse would satisfy the voltage control loop, and the converter would not command any more energy pulses until the output again drops below the lower voltage threshold.

At time t_3, the V_{gd} supply has dropped below its lower threshold, but V_{out} is still above its threshold point. This results in an energy pulse to the gate drive supply at t_4. However, while the gate drive is being serviced, V_{out} has dropped below its lower threshold, so the state machine commands an energy pulse to V_{out} as soon as the gate drive pulse is completed (time t_5).

Time t_6 represents a transition between light and heavy loads. A single energy pulse is not sufficient to force the output voltage above its upper threshold before the minimum off time has expired and a second charge cycle is commanded. Because the inductor does not reach zero current in this case, the peak current is greater than 0.5 A at the end of the next charge on time. The result is a ratcheting of inductor current until either the output voltage is satisfied, or the converter reaches its programmed current limit. At time t_7, the gate drive voltage has dropped below its threshold, but the converter continues to service V_{out} because it has highest priority, unless V_{gd} drops below 7.6 V.

Between t_7 and t_8, the converter reaches its maximum current limit that is determined by the programmed power limit and V_{in}. Once the limit is reached, the converter operates in continuous mode with approximately 200 mA of ripple current. A time t_8, the output voltage is satisfied, and the converter can service V_{gd}, which occurs at t_9.

Topology Extensions

The multiplexed coil topology can be extended to produce additional outputs. Figure 12 shows a single inductor providing

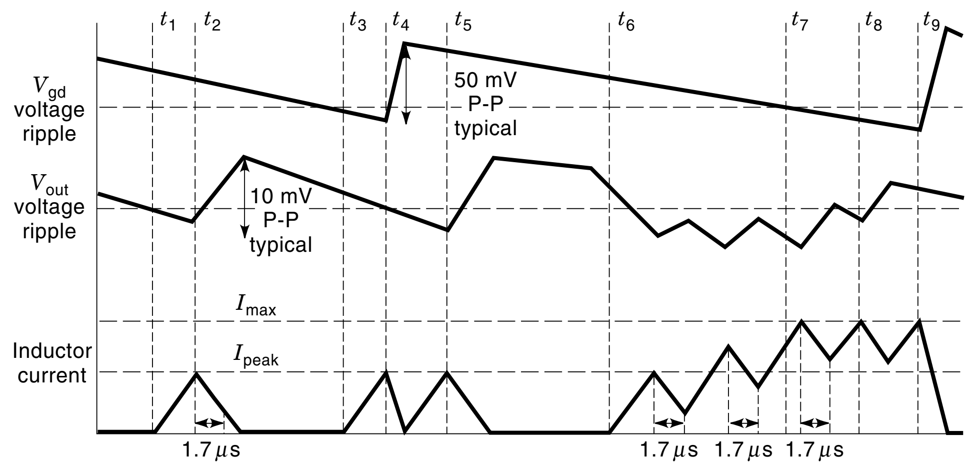


Figure 11. Multiplexed inductor servicing two outputs.

energy to three positive outputs and a negative output. The generation of the main output V_{out} and gate drive output V_{gd} has been explained. The V_{NiCd} output is a trickle charger for a nickel cadmium battery backup. In order to produce a fixed, low-current, trickle charge, the converter delivers low peak current pulses to the V_{NiCd} output at fixed intervals of time.

A negative voltage V_{neg} is produced by using a flyback technique with V_{out} and V_b. Negative current is generated by back-charging the inductor through the S_{out} switch. When the inductor current reaches some negative peak, S_{out} is open. Current is then pulled through D_{neg}, charging the V_{neg} output. For the flyback technique to operate correctly, the charge stored in the V_{out} capacitor should be several times larger than the charge stored in the V_{neg} capacitor.

CONCLUSION

When selecting a power management solution for a portable application, it is important that the converter operates efficiently over a wide dynamic range. In order to get the most energy from a low-voltage power source, the converter should be able to start up and operate below 1 V during peak load demands. When additional outputs are required, issues relating to converter efficiency and board real estate can often be critical.

The UCC3941 addresses these issues by incorporating an adaptive control scheme that extends the battery's usable voltage range. High efficiency over a wide dynamic load range is achieved with a constant power continuous current mode and a fixed peak current discontinuous mode. A unique power conversion topology is used, where multiple outputs are generated from a single inductor, resulting in efficient use of board space.

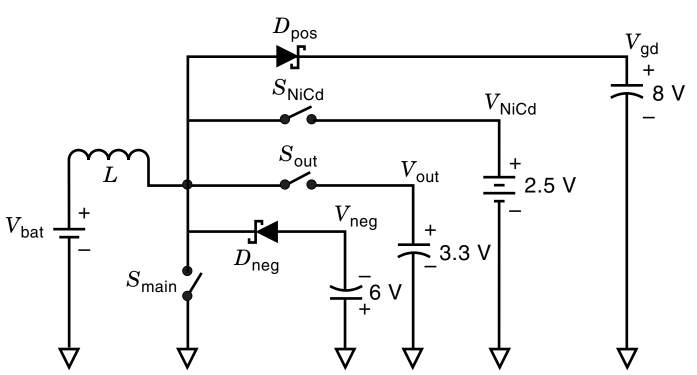


Figure 12. Single inductor servicing four outputs.

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SYNCHRONOUS GENERATORS.

See Hydroelectric generators.

SYNCHRONOUS MACHINE DRIVES.

See Synchronous motor drives.