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Designing a Boost-Switching Regulator with the MCP1650

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INTRODUCTION

Today's electronic circuits require a number of different voltage potentials. Powering silicon devices like microcontrollers or digital logic require a different voltage than bias supplies or powering strings of LEDs. A system can very easily contain a combination of circuits that require different voltages. With only a single input voltage delivered to the system, a power regulator is needed to produce the necessary voltages.

The power regulator can be an inductor-based, switch-mode power converter, a switched capacitor charge pump or a linear regulator. Each regulator has it's own advantages and disadvantages, but it is the particular application requirements that determine which type of power regulator is best suited.

This application note focuses on inductor-based, switchmode power converters, more specifically – the boost regulator topology. The boost is one of the fundamental switchmode power topologies. The other being the buck regulator. From these two topologies, all other switchmode power supply topologies are derived. The buck topology is used to provide a regulated voltage that is lower than the unregulated input voltage source. The boost topology produces a regulated output voltage that is higher than the unregulated input voltage source. An example of a boost regulator design will be explored using Microchip's MCP1650 boost controller.

UNDERSTANDING THE BOOST TOPOLOGY

Before we begin the design example, it is important to understand how the boost converter produces an output voltage that is always greater than the input voltage. In order to do this, we must analyze the boost circuits in Figure 1. During one switching cycle, the switch (S1) transitions between a closed and opened position. If the switching cycle begins with S1 in the closed position (as in Figure 1B), diode D_1 is reverse-biased, the voltage across the boost inductor (L_1) is equal to V_{IN} and the current is ramping up in L_1. Any load requirements during this phase are supplied by the output capacitor (C_1). When S1 switches to the open position, as in Figure 1C, D_1 is forward-biased, the voltage across L_1 is V_{IN} minus V_{OUT} and energy is transferred from L_1 (as well as the input source) to the load. The energy depleted from C_1 is also replaced. The output voltage is greater than the input because both the input source and L_1 supply energy to the load during this phase. A practical realization of the boost converter is illustrated in Figure 1D, where S1 is replaced by a N-channel MOSFET. A graphical representation of the boost waveforms can be found in Figure 2.
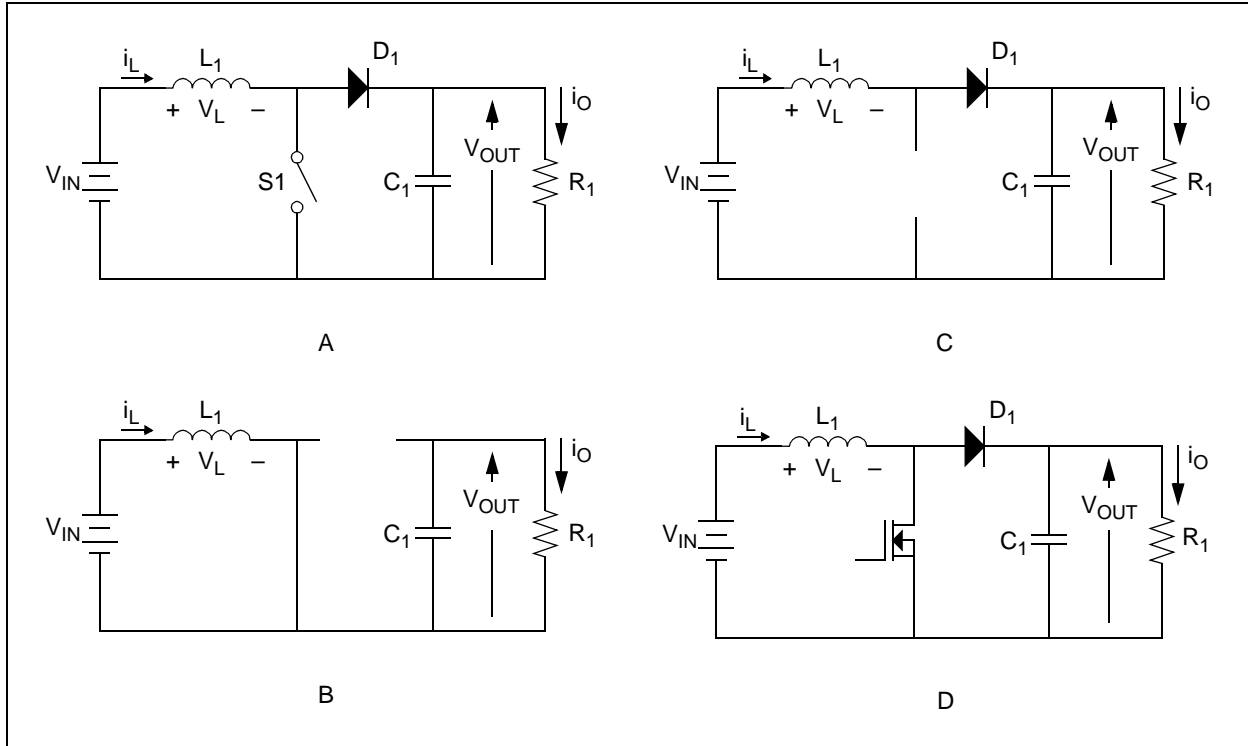
FIGURE 1:   *Basic Boost Topology.*

It can therefore be stated that the output voltage is generated by the switch opening and closing at a frequency of 1/T, where T is the switch cycle period. The ratio of the on-time to the switch cycle period is referred to as the duty cycle (D).

EQUATION 1:

$$D = \frac{t_{ON}}{T}$$

The switch period can also be defined as the switch on-time plus the switch off-time.

EQUATION 2:

$$T = t_{ON} + t_{OFF}$$

Boost Inductor

There are two possible modes of operation for the boost converter. To determine which mode of operation the boost converter is operating in, we must look at the inductor current at the end of the switching cycle. One situation occurs when there is still energy (or current) left in the inductor when the switch is closed. This is known as Continuous Current Mode (CCM) operation. The second situation occurs when all the energy (or current) stored in the inductor is transferred to the load before the switch is closed. This is known as Discontinuous Current Mode (DCM) operation.

The mode of operation is determined by the load current for fixed values of L_1 and duty cycle. As load current decreases, the mode of operation will change from CCM to DCM. To maintain CCM operation, the value of L_1 would have to proportionally increase as load current decreases.

By evaluating the boost converter while operating critically continuous, which is the boundary between CCM and DCM, we can determine for certain input/output requirements what inductor value is needed to ensure operation in CCM or DCM.

Figure 2 shows the boost converter waveforms when operating critically continuous. These waveforms will be used to determine the inductor value. To avoid saturating the inductor, the average voltage across the inductor must equal zero.

EQUATION 3:

$$(V_{IN} \cdot DT) + ((V_{IN} - V_{OUT}) \cdot (1 - D)T) = 0$$

It follows, then, that the relationship between the input voltage (V_{IN}) and the output voltage (V_{OUT}) can be described in terms of the switch duty cycle as:

EQUATION 4:

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

The link between the input current (I_{IN}) and output current (I_{OUT}) can also be defined in terms of the duty cycle, assuming that the output power is equal to the input power.

EQUATION 5:

$$\frac{I_{OUT}}{I_{IN}} = (1 - D)$$

By definition, critically continuous operation occurs when the inductor current reaches zero precisely at the end of t_{OFF}. The average inductor current is equal to one half the peak inductor ripple current. Mathematically, it is defined as:

EQUATION 6:

$$I_{Lboundary} = \frac{1}{2} \cdot \frac{V_{IN}}{L} \cdot t_{ON}$$

Where:

$I_{Lboundary}$ = the inductor current at the boundary of continuous/discontinuous operation.

It is desired to define this boundary condition in terms of the output requirements. This can be done by applying the relationship between D and t_{ON}, as well as V_{IN} and V_{OUT} to the equation above.

EQUATION 7:

$$I_{Lboundary} = \frac{1}{2} \cdot \frac{T \cdot V_{OUT}}{L} \cdot D(1 - D)$$

From the basic boost circuit, it can be seen that the average inductor current equals the average input current. Therefore, the boundary between CCM and DCM modes can be defined in terms of the output current.

EQUATION 8:

$$I_{OUTboundary} = \frac{1}{2} \cdot \frac{T \cdot V_{OUT}}{L} \cdot D(1 - D)^2$$

From this equation, the value of the inductor can be calculated to provide critically continuous operation. To achieve CCM operation, the inductor value chosen should be greater than $I_{OUTboundary}$. Likewise, for DCM, the inductor value should be less than $I_{OUTboundary}$.

Output Capacitor

The output capacitor must deliver energy to the load during the switch on-time and to filter the output ripple voltage. Since no energy is being supplied to the capacitor during this time interval, the output voltage will decrease from its original value at $t_{ON} = 0$. The value of the ripple voltage (ΔV_{OUT}) is typically a design requirement. Therefore, the value of the C_1 can be calculated by:

EQUATION 9:

$$C_1 = \frac{I_{OUT} \cdot \Delta T}{\Delta V_{OUT}}$$

There will also be some ΔV_{OUT} caused by the Equivalent Series Resistance (ESR) of the output capacitor. Though ceramic capacitors have a low ESR, they are relatively expensive in higher values. Tantalum and electrolytic capacitors have a higher ESR, but have lower cost in higher values. A trade-off must be made between ESR ripple voltage and component cost.
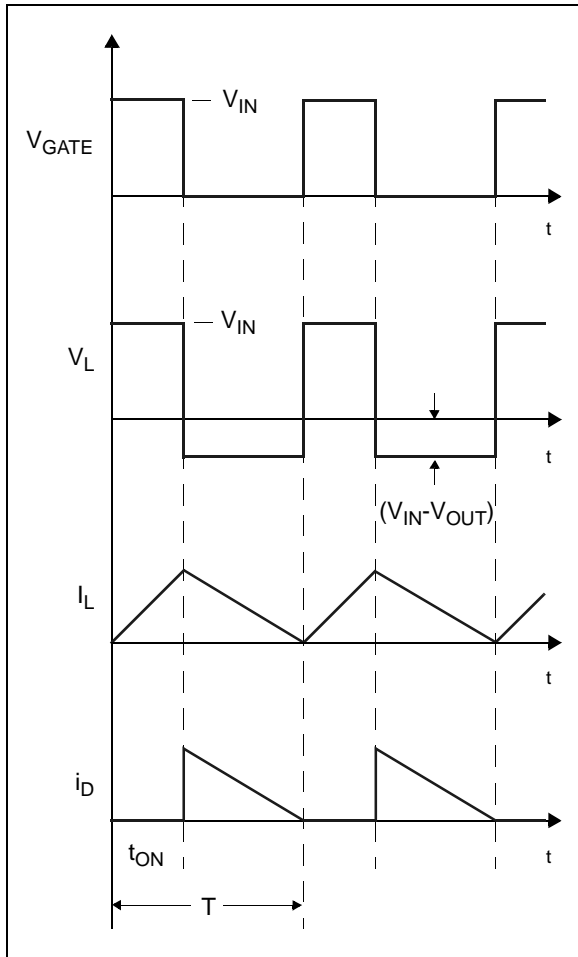
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FIGURE 2: *Critically Continuous Waveforms.*

DESIGNING WITH THE MCP1650

The MCP1650 utilizes a 750 kHz hysteretic gated oscillator architecture. No compensation components are required to stabilize the MCP1650 operation because of this hysteretic approach. The duty cycle of the MCP1650 is also limited to 56% or 80%, depending on the input voltage. For an input voltage between 2.7V and 3.8V, the duty cycle is 80%, whereas an input voltage between 3.8V and 5.5V has a duty cycle of 56%. By decreasing the duty cycle at higher input voltages, the peak input current is reduced.

Output voltage regulation is accomplished by comparing the output voltage that is sensed through an external resistor divider to a 1.22V reference internal to the device. When the sensed voltage is below the reference voltage, the external N-channel MOSFET is pulsed on and off at a gated oscillator frequency of 750 kHz. Several pulses may be required to deliver enough energy to pump the output voltage above the upper hysteretic limit. However, once the output voltage is above this limit, the external MOSFET is no longer pulsed on. This allows the output voltage to coast down below the hysteretic limit. This "pumping-up" of the output voltage is how the MCP1650 produces output voltages that would require a duty cycle different than the 56% or 80% duty cycle limits. The timing diagram in Figure 3 provides an illustration on how the MCP1650 gated oscillator architecture works.
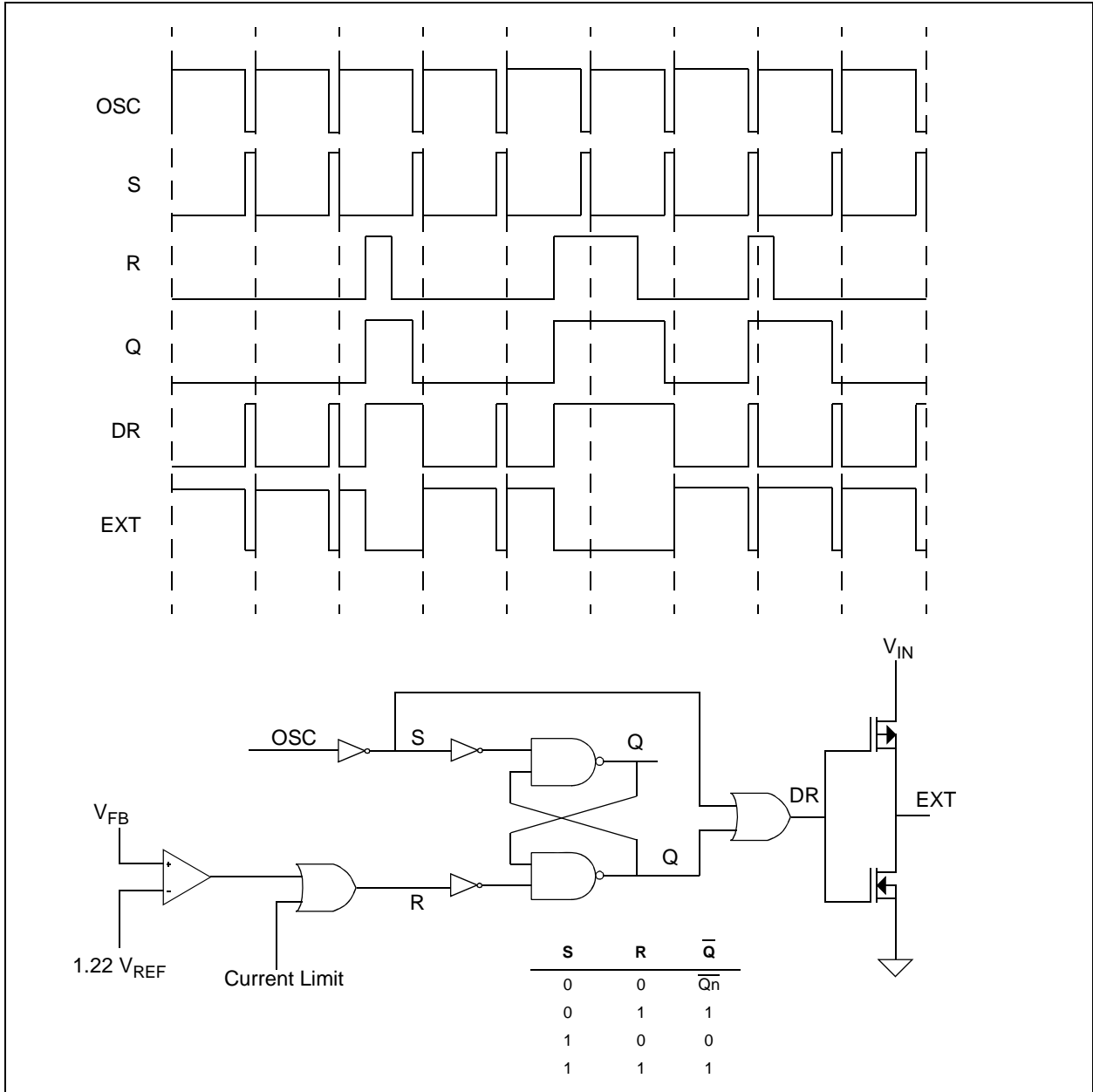
FIGURE 3: *Timing Diagrams.*
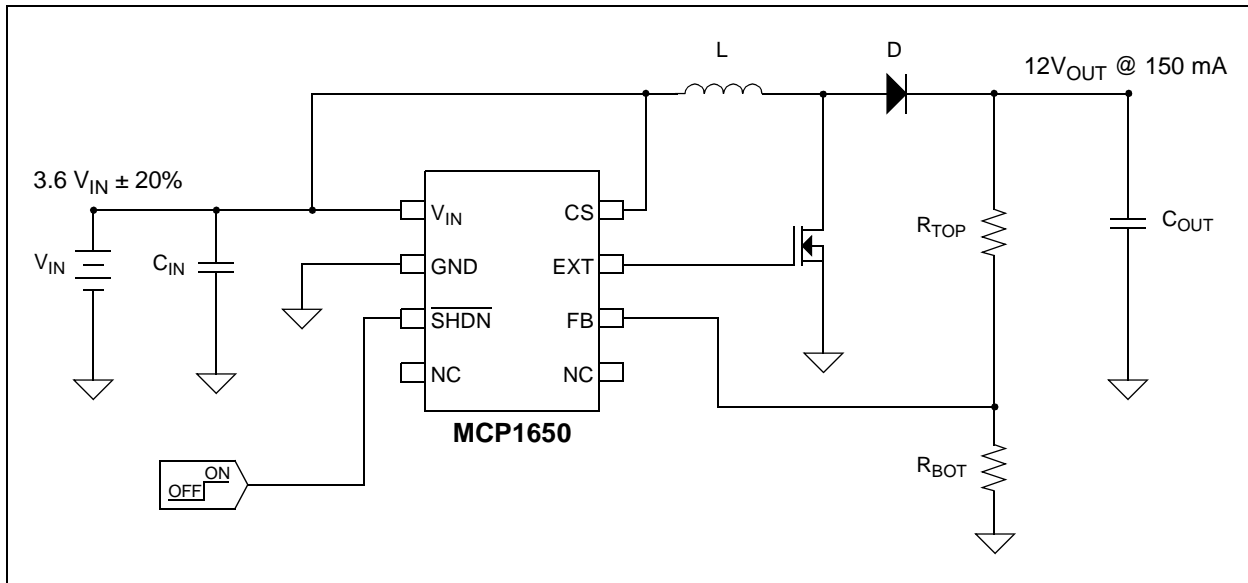
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Boost Regulator Design Example

FIGURE 4: *Boost Application Schematic.*

A practical boost regulator design example will be presented. Figure 4 shows the schematic of the boost regulator.

The design parameters are given as follows:

$$
\begin{aligned}
\text{Input Voltage} &= 3.6V \pm 20\% \\
\text{Output Voltage} &= 12V \\
\text{Output Current} &= 150\ mA \\
\text{Oscillator Frequency} &= 750\ kHz \\
\text{Duty Cycle} &= 80\% \text{ for } V_{IN} < 3.8V \\
\text{Duty Cycle} &= 56\% \text{ for } V_{IN} > 3.8V
\end{aligned}
$$

Output Voltage Setting

The first step in the design cycle is to determine the values for the external resistor divider that is used to provide the feedback voltage (V_{FB}) to the MCP1650. V_{FB} is compared internally to a 1.22V band gap reference.

EQUATION 10:

$$
R_{TOP} = R_{BOT} \times \left(\left(\frac{V_{OUT}}{V_{FB}} \right) - 1 \right)
$$

Where:

  R_{TOP} = Top Resistor Value

  R_{BOT} = Bottom Resistor Value

Due to the RC delay caused by the resistor divider and the device input capacitance, resistor values greater than 100 kΩ are not recommended.

For this example, the value of R_{BOT} will be set to 10 kΩ. It would then follow that R_{TOP} would equal 88.4 kΩ. However, the closest standard 1% value of 88.7 kΩ is selected.

As was discussed earlier, DCM occurs when all of the energy in the inductor is depleted before the next inductor charging cycle begins, which corresponds to the MOSFET turning on. It is important that the MCP1650 operate in DCM if a high boost ratio is required. To determine if the regulator must operate in DCM, simply calculate the maximum output voltage possible by using Equation 4. For the input voltage range used in this example, the MCP1650 runs at two different duty cycles. Therefore, both duty cycles need to be evaluated.

Calculating V_{OUT} for the minimum V_{IN}:

$$
V_{OUT} = \left(\frac{1}{1 - 0.8} \right) \times 2.88
$$
$$
V_{OUT} = 14.4V
$$

This satisfies our V_{OUT} requirement, but we must also check the case when the duty cycle is 56%. This corresponds to the cause when V_{IN} is 3.8V.

$$
V_{OUT} = \left(\frac{1}{1 - 0.56} \right) \times 3.8
$$
$$
V_{OUT} = 8.6V
$$

The value calculated for V_{OUT} when V_{IN} is 3.8V is less than the required value of 12V. This tells us that we need a boost regulator with a high boost ratio and, therefore, the regulator will need to operate in DCM. As can be seen in the timing diagram, operating in DCM allows for a pumping-up of the output voltage, helps minimize the gating of the oscillator and skipping inductor charging pulses.

Inductor Selection

An iterative energy balance approach will be used to determine the maximum inductance needed to maintain DCM operation. The energy going into the inductor, multiplied by the switching frequency, must be greater than the maximum input power. The input power is calculated assuming a regulator efficiency of 80%.

$$P_{IN} = P_{OUT}/(Efficiency)$$
$$P_{IN} = (V_{OUT} \times I_{OUT})/(Efficiency)$$
$$P_{IN} = (12 \times 0.15)/(0.8)$$
$$P_{IN} = 2.25W$$

Using a standard inductor value of 3.3 µH, the peak inductor current is calculated. This peak inductor current must be evaluated for both MCP1650 duty cycles.

$$I_{PK} = \frac{V_{IN}}{L} \times T_{ON}$$
$$I_{PK} = \frac{V_{IN}}{L} \times \left(\frac{1}{F_{SW}} \times D\right)$$
$$I_{PK}(2.88V_{IN}) = \frac{2.88}{3.3 \times 10^{-6}} \times \left(\frac{1}{750 \times 10^3} \times 0.8\right)$$
$$I_{PK}(2.88V_{IN}) = 931mA$$
$$I_{PK}(3.8V_{IN}) = \frac{3.8}{3.3 \times 10^{-6}} \times \left(\frac{1}{750 \times 10^3} \times 0.56\right)$$
$$I_{PK}(3.8V_{IN}) = 860mA$$

The minimum V_{IN} is used for each duty cycle because, as V_{IN} is raised, the peak inductor current also increases. Therefore, the energy in the inductor increases. The energy in the inductor is given as:

$$Energy = \frac{1}{2} \times L \times I_{PK}^2$$
$$Energy(2.88V_{IN}) = 0.5 \times 3.3 \times 10^{-6} \times (0.931)^2$$
$$Energy(2.88V_{IN}) = 1.43\mu J$$
$$Energy(3.8V_{IN}) = 0.5 \times 3.3 \times 10^{-6} \times (0.86)^2$$
$$Energy(3.8V_{IN}) = 1.22\mu J$$

To find the power in the inductor, the energy is multiplied by the switching frequency.

$$P = Energy \times F_{SW}$$
$$P_{IND}(2.88V_{IN}) = 1.43 \times 10^{-6} \times 750 \times 10^3$$
$$P_{IND}(2.88V_{IN}) = 1.07W$$
$$P_{IND}(3.8V_{IN}) = 1.22 \times 10^{-6} \times 750 \times 10^3$$
$$P_{IND}(3.8V_{IN}) = 0.915W$$

Recall that the input power to the regulator was calculated as 2.25W. So, for a high boost ratio application, the regulator needs to operate in DCM. This means that the inductor power must be greater than the input power. In this example, the inductor power is less than the input power and, therefore, the inductance needs to be decreased to achieve DCM.

If a 1.2 µH inductor is used:

$$I_{PK}(2.88V_{IN}) = 2.52A$$
$$Energy(2.88V_{IN}) = 3.87\mu J$$
$$P_{IND}(2.88V_{IN}) = 2.90W$$
$$I_{PK}(3.8V_{IN}) = 2.33A$$
$$Energy(3.8V_{IN}) = 3.30\mu J$$
$$P_{IND}(3.8V_{IN}) = 2.47W$$

Now the power in the inductor is always greater than the regulator input power and the regulator will operate in DCM. One important item to note is that, as the inductance decreases, the peak current drawn from the input increases. The best choice of inductance for high boost ratios is the maximum inductance necessary to maintain DCM.

Output Capacitor Selection

The output capacitor must be sized to provide energy to the load during the MOSFET on-time. Since the capacitor energy is not being replenished during this time, the output voltage will have a decreasing slope during the MOSFET on-time. During the MOSFET off-time, energy is being replenished to the capacitor and the output voltage will have an increasing slope. This maximum change in V_{OUT} is usually a design requirement specified as a maximum output ripple voltage. By using Equation 9, the capacitance needed to satisfy the output ripple voltage requirement can be found. As mentioned before, the ESR of the capacitor should be low. Ceramic capacitors have low ESR, but are slightly more expensive than tantalum or electrolytic capacitors.

Boost Diode Selection

For most applications, a Schottky diode is recommended for the boost diode since fast turn-on and turn-off times are required. The voltage rating of the Schottky diode must be rated for the maximum output voltage. Schottky diodes also have a low forward voltage drop (V_{FD}) characteristic. A 20V or 30V Schottky diode is recommended for a 12V application.

MOSFET Selection

There are two requirements of the N-channel MOSFET that need to be evaluated. One is the drain-to-source voltage rating. The V_{DS} of the MOSFET must be rated to handle V_{OUT} plus the forward drop of the external boost diode (V_{FD}). For this example, V_{OUT} is 12V and V_{FD} of a Schottky diode is typically 0.5V. Therefore, the MOSFET V_{DS} rating must be greater than 12.5V. Typically, a 20V MOSFET can be used for 12V outputs.

The MOSFET should also have a low drain-to-source resistance (R_{DSon}). The drive capability of the MCP1650 is equal to the device input voltage. Therefore, for this example, the MOSFET should have a low R_{DSon} with a gate drive voltage of 2.8V. Also, the MOSFET carries current during the on-time and, during this period of operation, the peak current in the MOSFET can get quite high. Ideally, the MOSFET would have as low an R_{DSon} as possible and, therefore, help increase the overall efficiency of the regulator. However, this is not always the case since, as the R_{DSon} decreases, the total gate charge increases. This gate charge increase causes a slower transition time of the MOSFET, resulting in increased switching losses.

Input Capacitor Selection

There are no special requirements on the input capacitor. It's size is dependant on the source impedance of the particular application. The hysteretic architecture can draw relatively high input current peaks at certain line and load conditions. The input capacitor helps supply energy to the regulator and reduce the current spikes seen by the source. Small input capacitors can produce a large ripple voltage at the input of the regulator, resulting in unsatisfactory performance. For the example used here, a 10 µF ceramic capacitor is sufficient because the load current is only 150 mA. For applications that require higher load currents, the input capacitance should be raised from this value.

Peak Current Protection

The MCP1650 has internal peak current protection circuitry. The external switch current is sensed on the Current Sense pin (CS) across an optional external resistor. If the voltage at the CS pin falls more than 122 mV below V_{IN}, the current-limit comparator is set and the pulse is terminated. This prevents the current from getting too high and damaging the MOSFET. This feature can be bypassed by connecting V_{IN} directly to the CS pin. Due to the path from input through the boost inductor and boost diode to output, the boost topology can not support a short circuit without additional circuitry. This is typical of all boost regulators.

Conclusion

Boost switchmode power topologies are used to step-up a given source voltage to a higher regulated load voltage. The MCP1650 makes the design of a boost regulator very easy since only two duty cycles need to be considered during the design procedure. Also, since an external MOSFET is used, the designer has the freedom to select a MOSFET that is optimum for the particular application.

A basic approach to aide in the understanding of the boost topology operation was presented. Mathematical equations were derived for the key boost components.

References

1. N. Mohan, T. Undeland, and W. Robbins, "*Power Electronics: Converters, Application, and Design",* New York: John Wiley and Sons, Inc., 1995.

2. MCP1650/51/52/53 Data Sheet, *"750 kHz Boost Controller"*, DS21876, Microchip Technology Inc., 2004

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