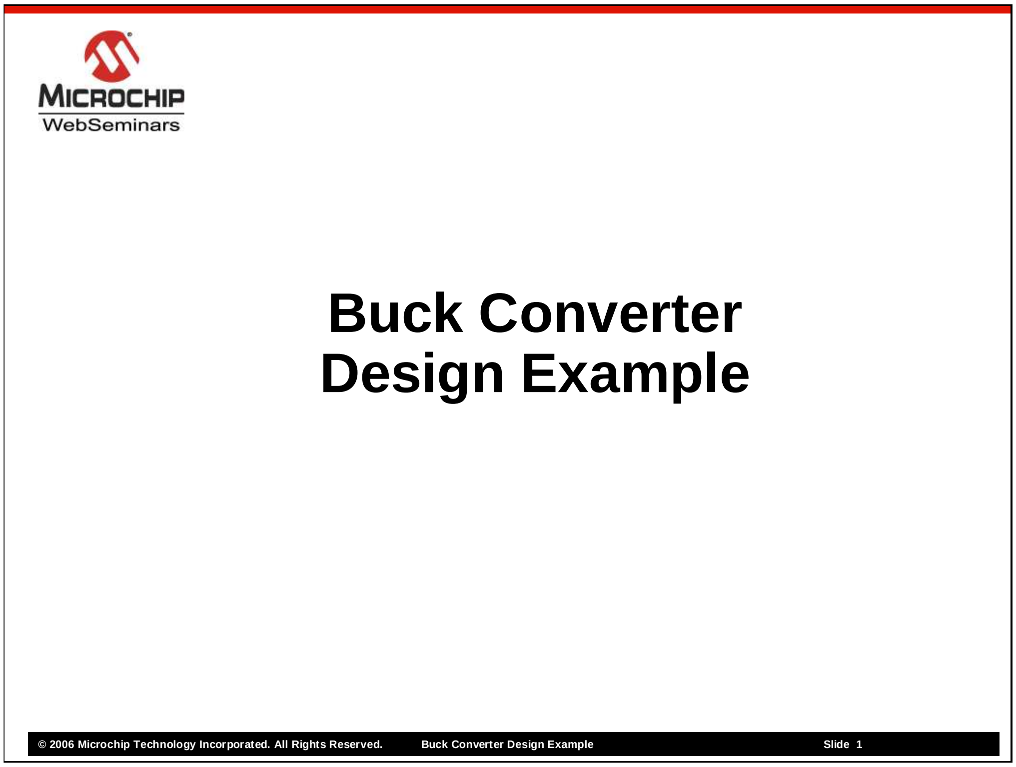

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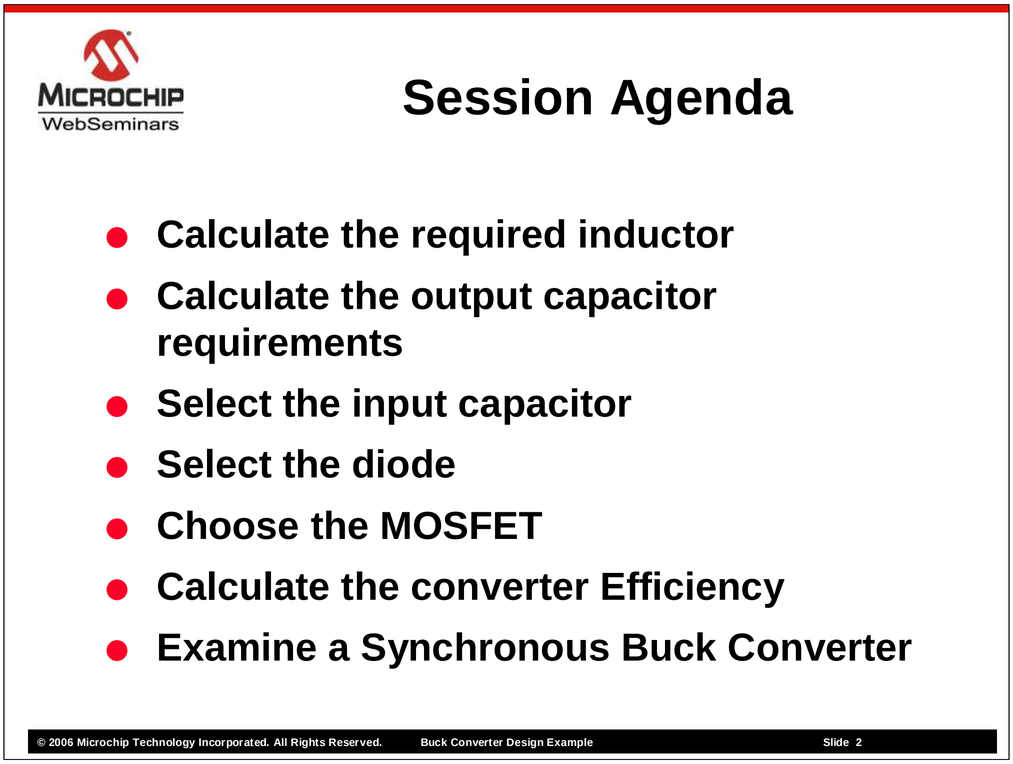
Buck Converter Design Example

Welcome to the Buck Converter Design Example Web seminar.

The following slides will show a process to calculate the component values needed for a Buck converter.



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Session Agenda

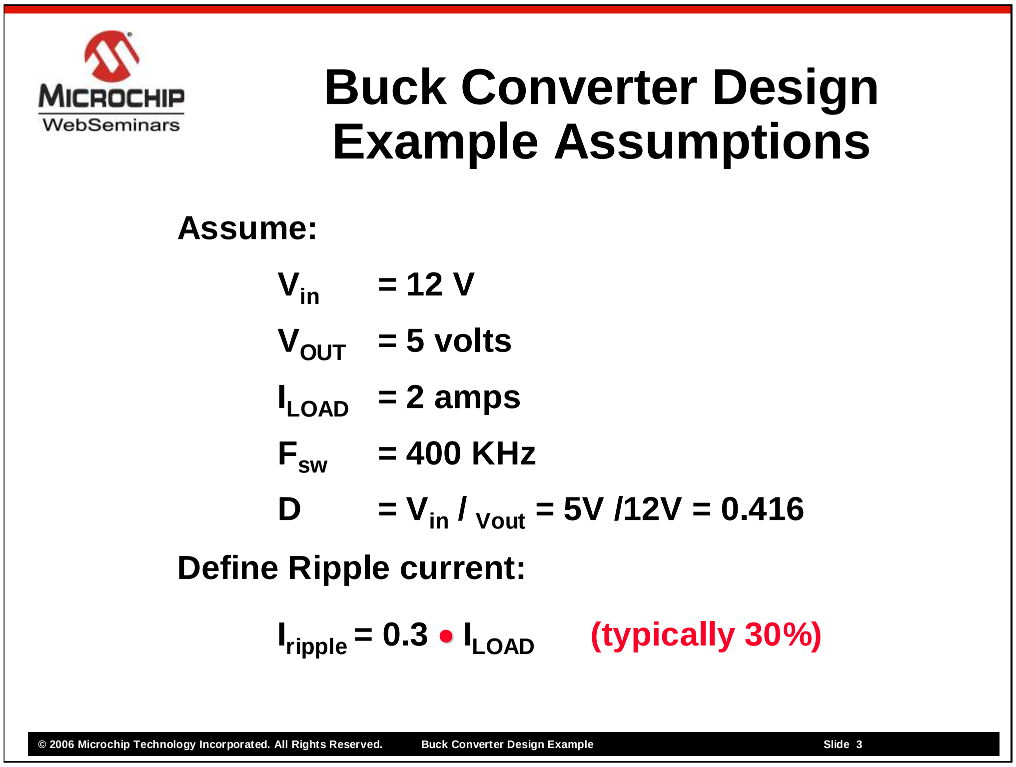
- Calculate the required inductor
- Calculate the output capacitor requirements
- Select the input capacitor
- Select the diode
- Choose the MOSFET
- Calculate the converter Efficiency
- Examine a Synchronous Buck Converter

This is the agenda for this course.

For a Buck DC-DC converter we will calculate the required inductor and output capacitor specifications.

We will then determine the input capacitor, diode, and MOSFET characteristics.

With the selected components, we will calculate the system efficiency and then compare this asynchronous design to a synchronous buck converter.



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Buck Converter Design Example Assumptions

Assume:

V_{in} = 12 V

V_{OUT} = 5 volts

I_{LOAD} = 2 amps

F_{SW} = 400 KHz

D = V_{in} / V_{out} = 5V /12V = 0.416

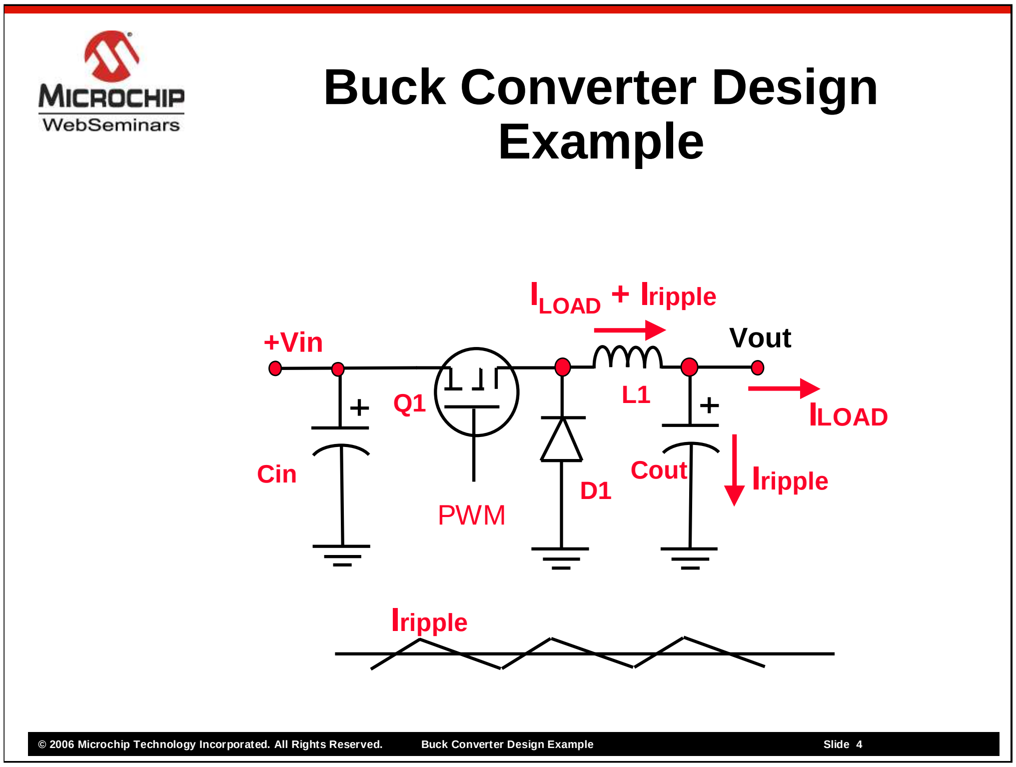
Define Ripple current:

$I_{ripple} = 0.3 \bullet I_{LOAD}$ (typically 30%)

This example converts a 12 volt power source to an output of 5 volts and 2 amps load.

The switching frequency is selected at 400 KHz.

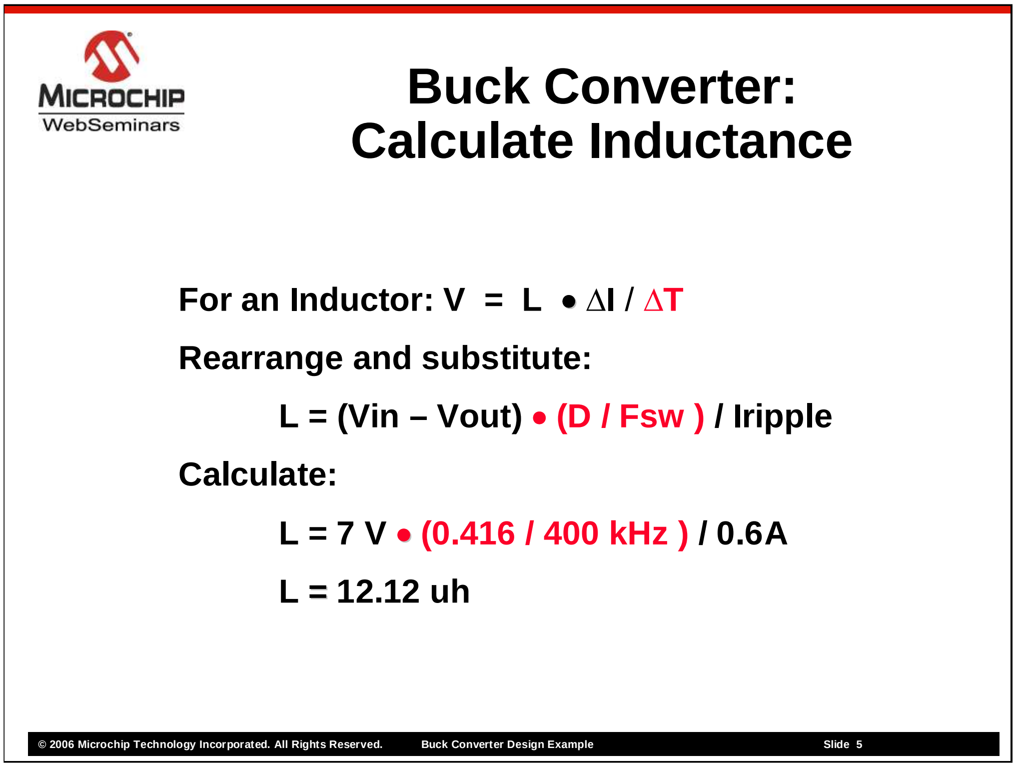
The current ripple will be limited to 30% of maximum load.



Buck Converter Design Example

Here is the schematic of the buck converter for which we will select component values.

In this example either a P-channel or an N-channel MOSFET may be used. The choice will be based on cost and complexity issues.



Buck Converter: Calculate Inductance

For an Inductor: $V = L \bullet \Delta I / \Delta T$

Rearrange and substitute:

$L = (Vin - Vout) \bullet (D / Fsw) / Iripple$

Calculate:

$L = 7\ V \bullet (0.416 / 400\ kHz) / 0.6A$

$L = 12.12\ uh$

Starting with the basic equation for current flow through an inductor:

$$V = L\ di/dt$$

We rearrange the terms to calculate “L” so :

$$L = V\ dt/di$$

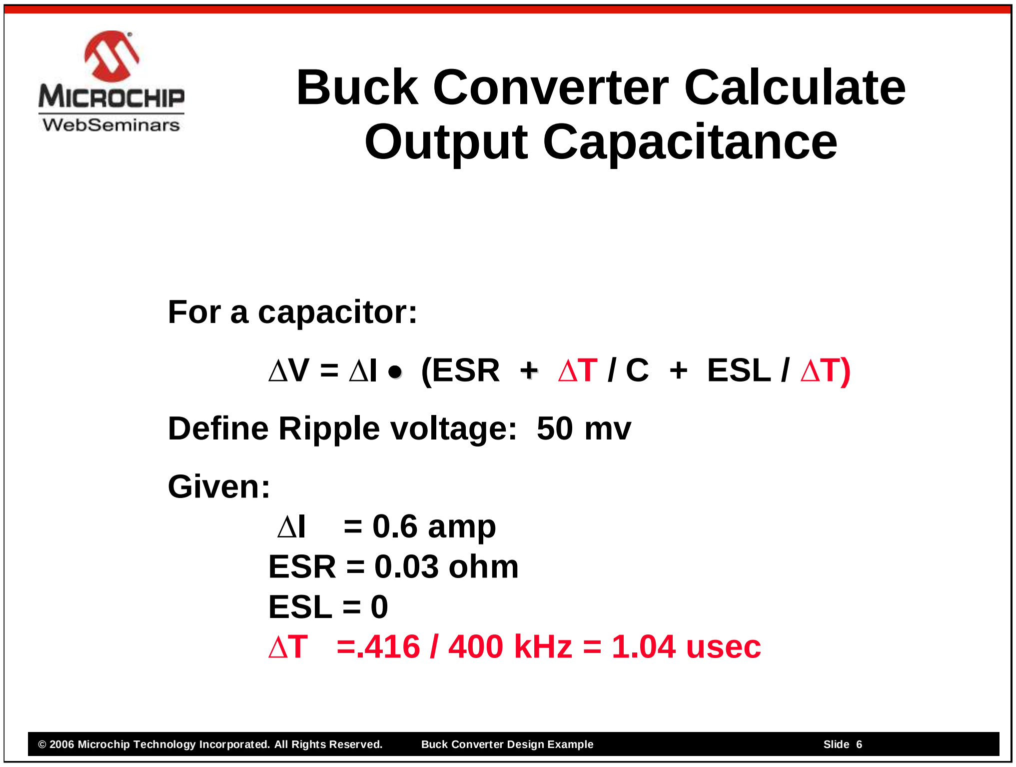
For the design example, the calculated inductor value is 12 uh.

From a catalog, a 12 uH, 3 amp inductor has a resistance of 0.037 ohm and costs about 85¢.

The power dissipated due to copper losses is:

$(I_{load})^2 \bullet ESR = 0.15$ **watt**

Note: The vendor information on core loss characteristics are often difficult to find.



Buck Converter Calculate Output Capacitance

For a capacitor:

$$\Delta V = \Delta I \bullet (ESR + \Delta T / C + ESL / \Delta T)$$

Define Ripple voltage: 50 mv

Given:

$\Delta I = 0.6$ amp
$ESR = 0.03$ ohm
$ESL = 0$
$\Delta T = .416 / 400$ kHz $= 1.04$ usec

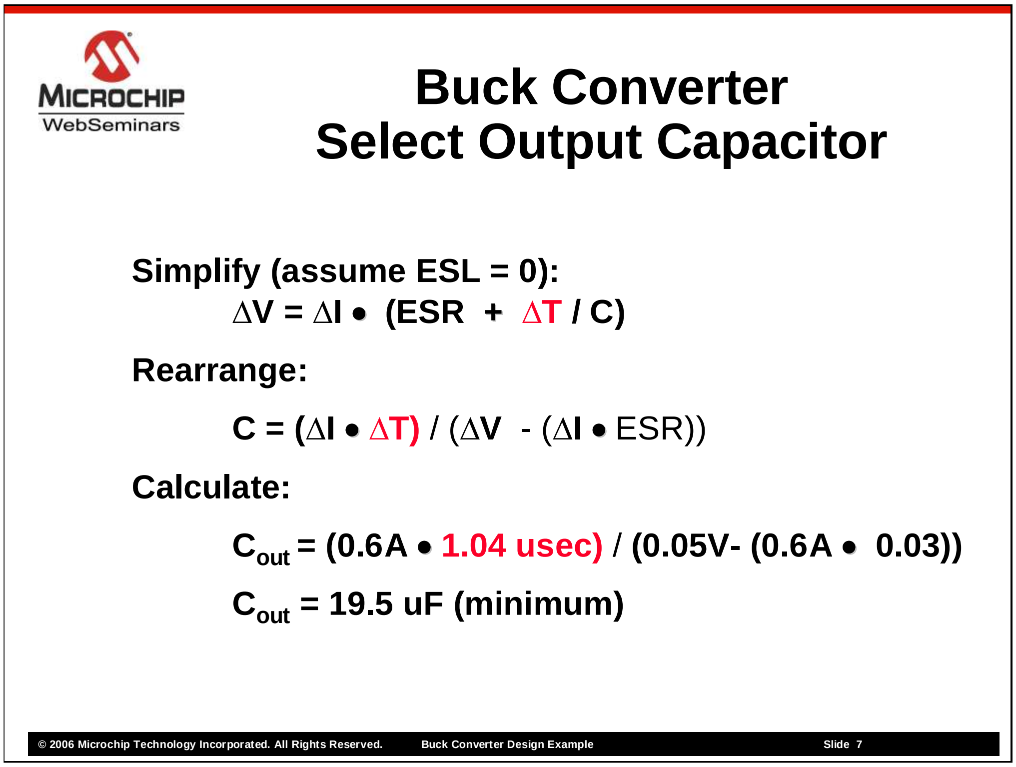
The voltage ripple across the output capacitor is the sum of ripple voltages due to the Effective Series resistance (ESR), the voltage sag due to the load current that must be supplied by the capacitor as the inductor is discharged, and the voltage ripple due to the capacitor's Effect Series Inductance".

The ESL specification is usually not specified by the capacitor vendor. For this example, we will assume that the ESL value is zero. As switching frequencies increase, the ESL specification will become more important.

The equation shown here shows that we are solving an equation with multiple unknowns, ESR, C, and ESL.

A reasonable approach is to remove terms that are not significant, and then make a reasonable estimate of the most important parameter that you can control, ESR.

The capacitor ESR value was selected from a vendor's catalog of smps rated capacitors. Given the ripple current and the target output voltage ripple, an ESR value of 0.030 ohm was selected from a list of capacitors rated for 0.6 amp ripple current.



Buck Converter
Select Output Capacitor

Simplify (assume ESL = 0):

$$\Delta V = \Delta I \bullet (ESR + \Delta T / C)$$

Rearrange:

$$C = (\Delta I \bullet \Delta T) / (\Delta V - (\Delta I \bullet ESR))$$

Calculate:

$$C_{out} = (0.6A \bullet 1.04\ usec) / (0.05V - (0.6A \bullet 0.03))$$

$$C_{out} = 19.5\ uF\ (minimum)$$

Now, we will calculate the required capacitance of the output capacitor given the desired output voltage ripple is defined as 50 millivolts.

The term in the equation's denominator ($\Delta V - (\Delta I \bullet ESR)$) shows that the capacitor's ESR rating is more important than the capacitance value. If the selected ESR is too large, the voltage due to the ripple current will equal or exceed the target output voltage ripple. We will have a divide by zero issue, indicating that an infinite output capacitance is required.

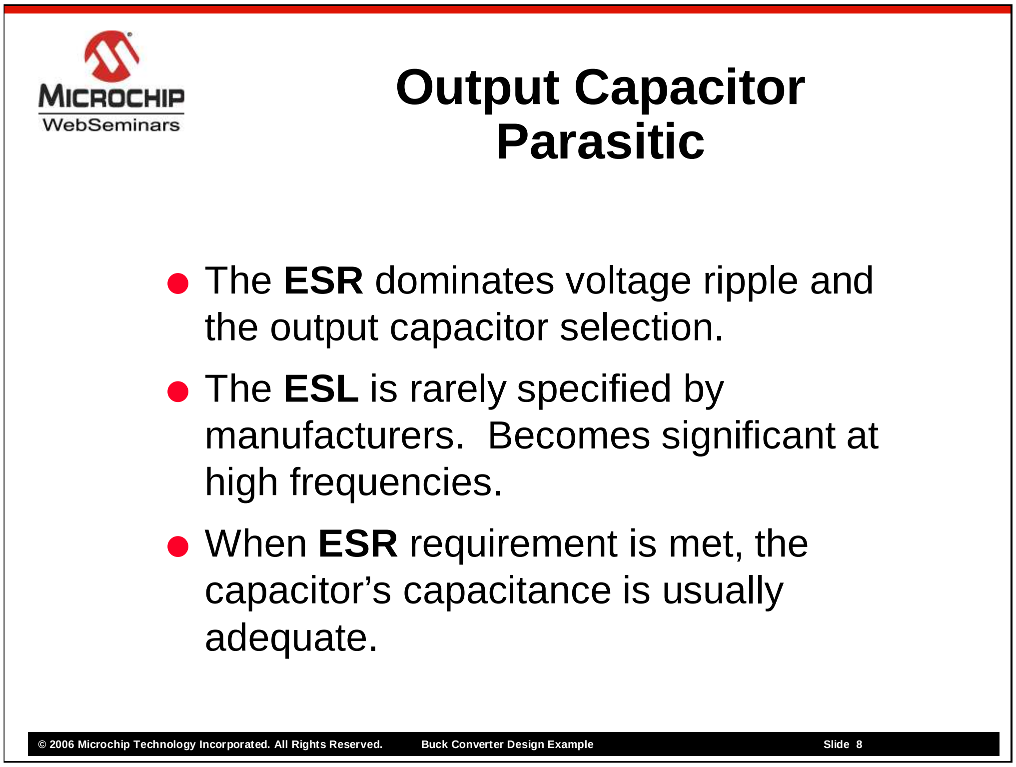
If a reasonable ESR is selected, then the actual capacitance value is reasonable.

An electrolytic capacitor with the require ESR has a capacitance of 1,200 uf which easily meets the minimum requirements and costs 12¢.

There are specialty polymer electrolytic capacitors with 47 uf, and an ESR of 0.025 ohm that are much smaller, but cost about $1.00.

The estimated power dissipation in the output capacitor is:

$$(Iripple)^2 \bullet ESR = 0.01\ watt$$



Output Capacitor Parasitic

- The **ESR** dominates voltage ripple and the output capacitor selection.
- The **ESL** is rarely specified by manufacturers. Becomes significant at high frequencies.
- When **ESR** requirement is met, the capacitor’s capacitance is usually adequate.

Estimate the maximum ESR your application can tolerate due to output voltage ripple requirements.

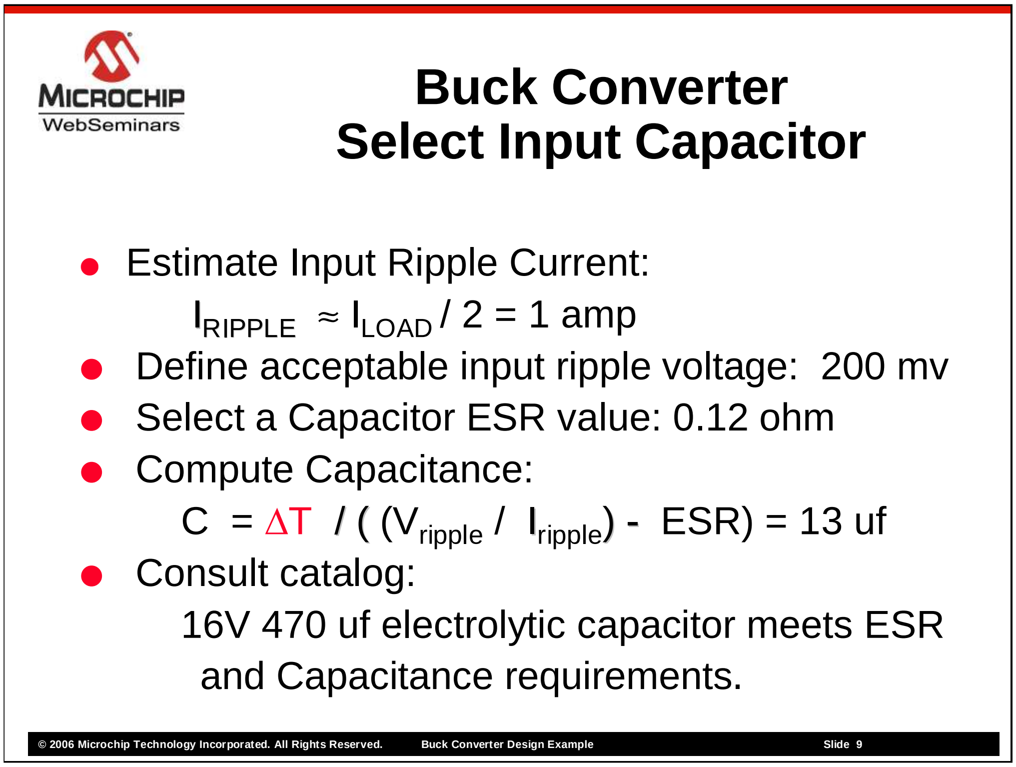
Make sure the capacitor is rated for the ripple current.

If operating at high switching frequencies (>1 MHz) contact the manufacturer to determine the ESL specifications for the capacitors you are considering to use. When considering ESL, also include the ESL of the PCB traces that interconnect the capacitor with the other components.

Rarely is the capacitor’s capacitance value an issue when operating at moderate frequencies. (> 100 KHz).

Exotic capacitors such as specialty electrolytics, large ceramics, or film capacitors are useful is space limited applications.

These advanced capacitors feature extremely low ESR for their small size, BUT, their small size implies a very limited capacitance. The limited capacitance of advanced capacitors may create issues with system stability and voltage “droop”..



Buck Converter
Select Input Capacitor

- Estimate Input Ripple Current:
  $I_{RIPPLE} \approx I_{LOAD} / 2 = 1$ amp
- Define acceptable input ripple voltage: 200 mv
- Select a Capacitor ESR value: 0.12 ohm
- Compute Capacitance:
  $C = \Delta T \ / \ ((V_{ripple} / I_{ripple}) - ESR) = 13$ uf
- Consult catalog:
  16V 470 uf electrolytic capacitor meets ESR and Capacitance requirements.

The worst case ripple current occurs when the duty cycle is 50% and the worst case ripple current on the input of a buck converter is about one half of the load current.

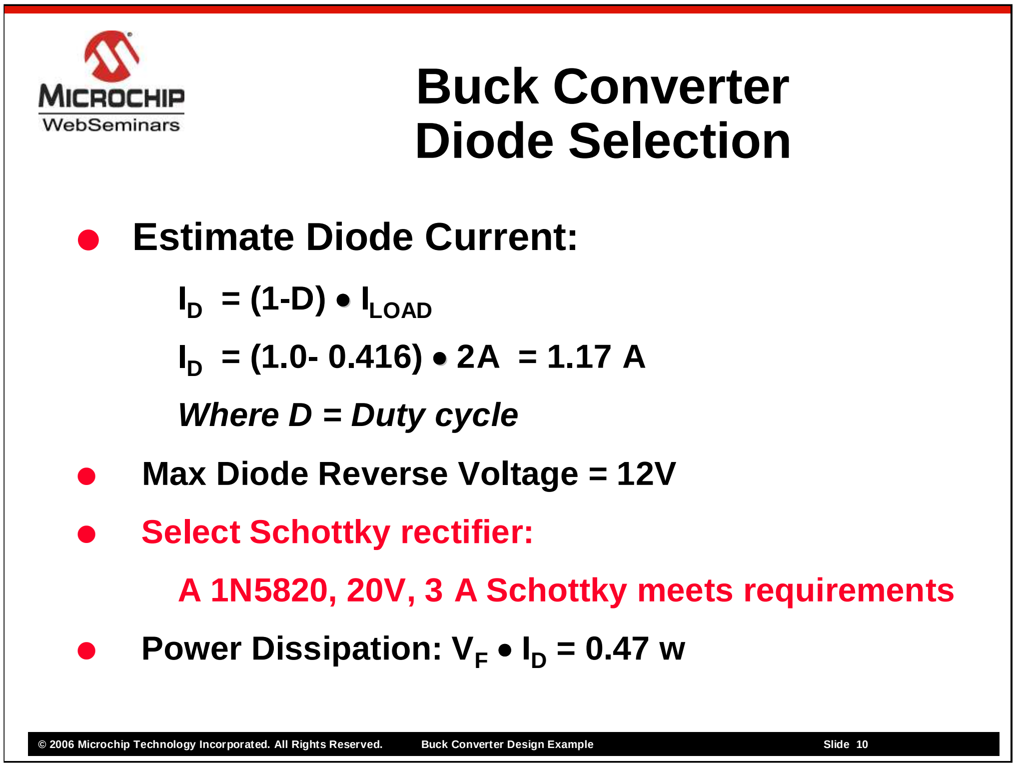
Like the output capacitor, the input capacitor selection is primarily dictated by the ESR requirement needed to meet voltage ripple requirements. Usually, the input voltage ripple requirement is not as stringent as the output voltage ripple requirement. In this example, the maximum input voltage ripple was defined as 200 millivolts.

The input ripple current rating for the input capacitors may be the most important criteria for selecting the input capacitors. Often the input ripple current will exceed the output ripple current.

From a catalog, a 16V, 470 uf electrolytic capacitor meets the ESR and ripple current requirements for 8¢.

The estimated power dissipation in the input capacitor is:

(Iripple)^2 • ESR = 0.12 watt



Buck Converter Diode Selection

- **Estimate Diode Current:**

  $I_D = (1\text{-}D) \bullet I_{LOAD}$

  $I_D = (1.0\text{-}\ 0.416) \bullet 2A = 1.17\ A$

  Where D = Duty cycle

- **Max Diode Reverse Voltage = 12V**
- **Select Schottky rectifier:**

  A 1N5820, 20V, 3 A Schottky meets requirements

- **Power Dissipation:** $V_F \bullet I_D = 0.47$ **w**

The diode’s average current is equal to the load current times the portion of time the diode is conducting.

The time the diode is on is: **(1 – duty cycle)**

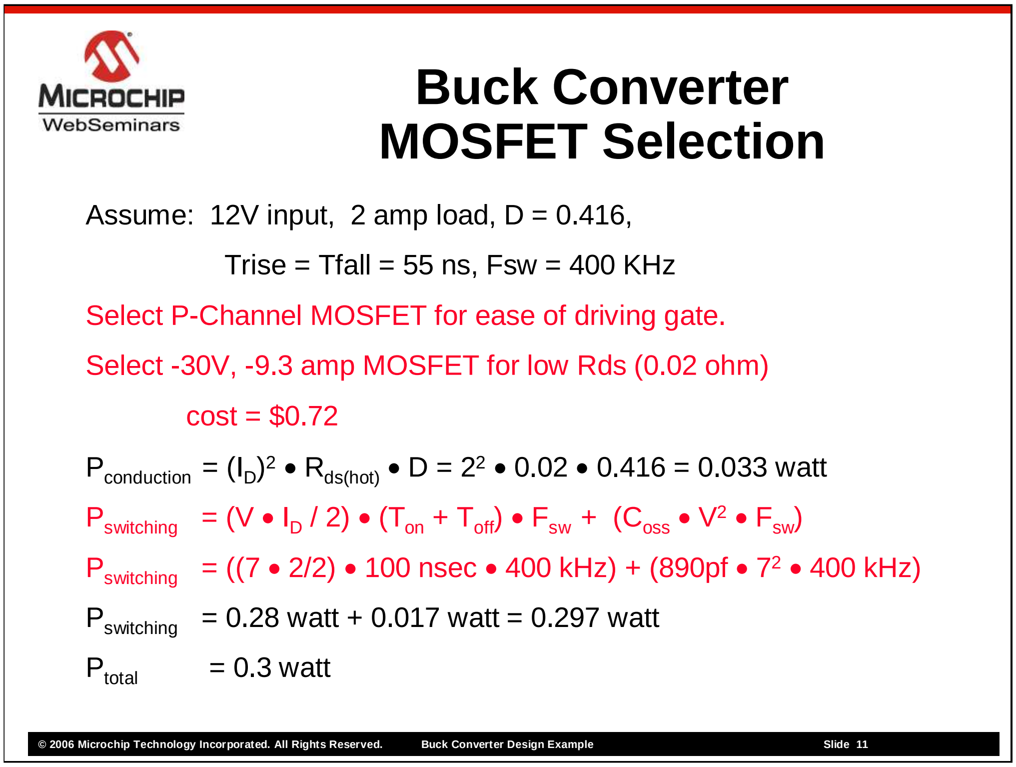
The maximum reverse voltage on the diode is Vin which is 12 volts in this example.

The current and voltage ratings are low enough that a small schottky diode can be used for this application.

By using a schottky diode, switching losses are negligible.

The forward voltage drop for the selected diode is about 0.4 volts at the peak current of 2.0 amps.

The estimated diode power dissipation is 0.47 watts.



Buck Converter MOSFET Selection

Assume: 12V input, 2 amp load, D = 0.416,

Trise = Tfall = 55 ns, Fsw = 400 KHz

Select P-Channel MOSFET for ease of driving gate.

Select -30V, -9.3 amp MOSFET for low Rds (0.02 ohm)

cost = $0.72

$P_{conduction} = (I_D)^2 \bullet R_{ds(hot)} \bullet D = 2^2 \bullet 0.02 \bullet 0.416 = 0.033$ watt

$P_{switching} = (V \bullet I_D / 2) \bullet (T_{on} + T_{off}) \bullet F_{sw} + (C_{oss} \bullet V^2 \bullet F_{sw})$

$P_{switching} = ((7 \bullet 2/2) \bullet 100$ nsec $\bullet$ 400 kHz) + (890pf $\bullet$ $7^2 \bullet$ 400 kHz)

$P_{switching} = 0.28$ watt + 0.017 watt = 0.297 watt

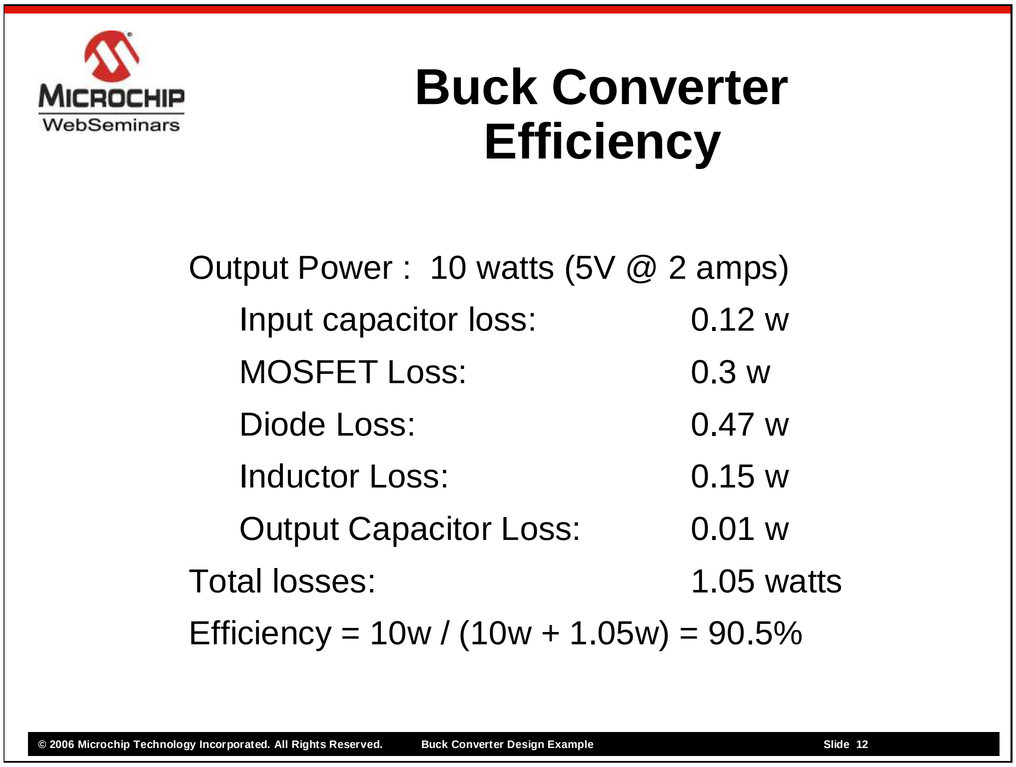
$P_{total} = 0.3$ watt

To simplify the gate drive circuitry for the MOSFET, a P-channel device was selected. An N-channel device would require a gate drive circuit that incorporates a method to drive the gate voltage about the source. The cost of a level translator and charge pump will outweigh the savings of using an N-channel device versus a P-channel device.

A 20 volt MOSFET was not selected because the available devices in the catalog had maximum gate to source voltage ratings of only 12 volts. With a 12 volt input voltage, the applied gate volts might exceed the device specifications. If a 20 volt MOSFET was used, it would be good design practice to incorporate a voltage clamp in the gate driver circuit.

A 30 volt device was selected on the basis of the 20 volt gate to source specification.

The device current rating is more than necessary, but the low Rds(on) specification minimizes temperature rise. Most small surface mount packages have thermal resistances of about 50 degrees Celsius per watt. With a calculated power dissipation of 0.3 watt, the MOSFET should experience a temperature rise of only 15 degrees C.



Buck Converter Efficiency

Output Power : 10 watts (5V @ 2 amps)

Input capacitor loss:	0.12 w
MOSFET Loss:	0.3 w
Diode Loss:	0.47 w
Inductor Loss:	0.15 w
Output Capacitor Loss:	0.01 w
Total losses:	1.05 watts

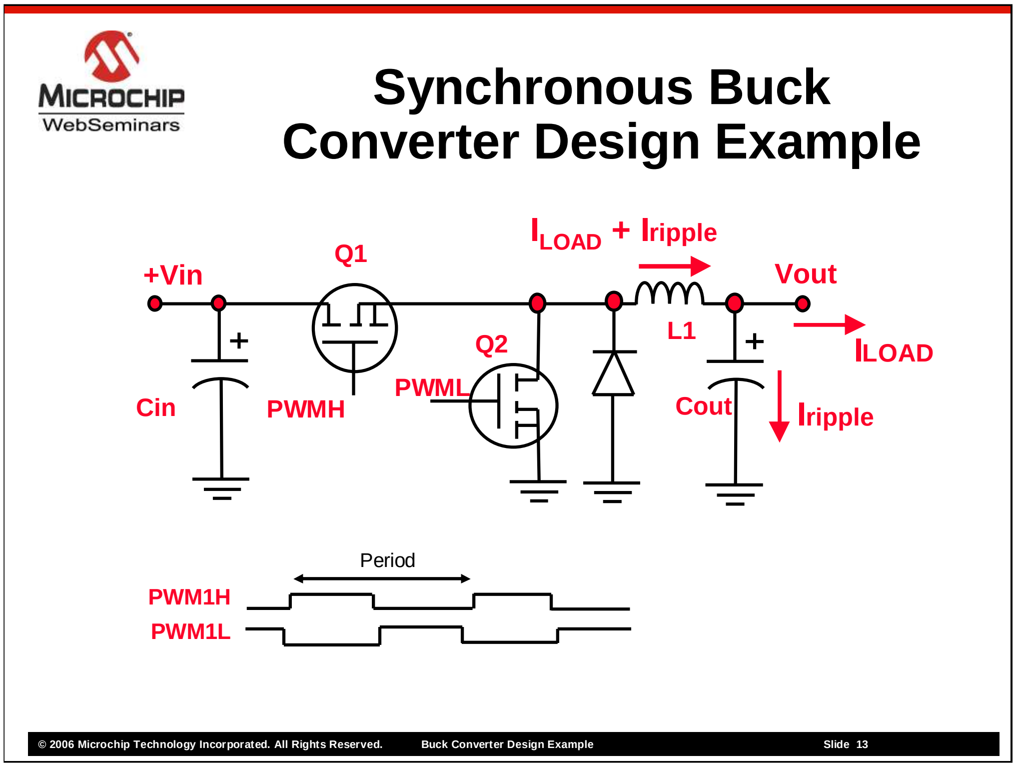
Efficiency = 10w / (10w + 1.05w) = 90.5%

This Buck converter design example has a calculated efficiency of 90.5%.

The diode losses represent almost one half of the total losses !

If the diode’s forward voltage drop could be lowered, the converter’s efficiency could be raised.

This buck converter design example is called an Asynchronous Buck converter because the diode commutation (switching) is independent of the MOSFET switching.



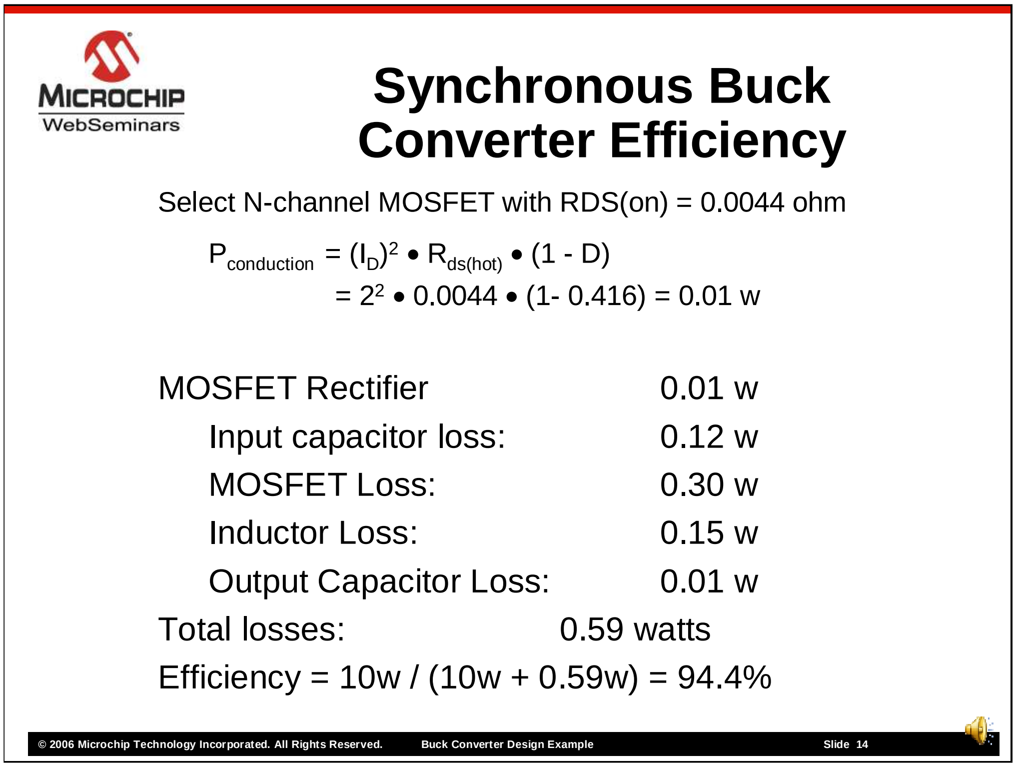
Synchronous Buck Converter Design Example

Buck Converter Design Example Slide 13

This slide shows a Synchronous Buck converter. It is similar to the previous asynchronous buck converter except the diode is paralleled with another transistor. It is called a synchronous buck converter because transistor Q2 is switched on and off synchronously with the operation of the primary switch Q1.

The idea of a synchronous buck converter is to use a MOSFET as a rectifier that has very low forward voltage drop as compared to a standard rectifier. By lowering the diode’s voltage drop, the overall efficiency for the buck converter can be improved.

The synchronous rectifier (MOSFET Q2) requires a second pwm signal that is the complement of the primary PWM signal. Q2 is on when Q1 is off and vice a versa. This pwm format is called Complementary PWM.



Synchronous Buck Converter Efficiency

Select N-channel MOSFET with RDS(on) = 0.0044 ohm

$$P_{conduction} = (I_D)^2 \bullet R_{ds(hot)} \bullet (1 - D)$$
$$= 2^2 \bullet 0.0044 \bullet (1- 0.416) = 0.01 \text{ w}$$

MOSFET Rectifier	0.01 w
Input capacitor loss:	0.12 w
MOSFET Loss:	0.30 w
Inductor Loss:	0.15 w
Output Capacitor Loss:	0.01 w
Total losses:	0.59 watts

Efficiency = 10w / (10w + 0.59w) = 94.4%

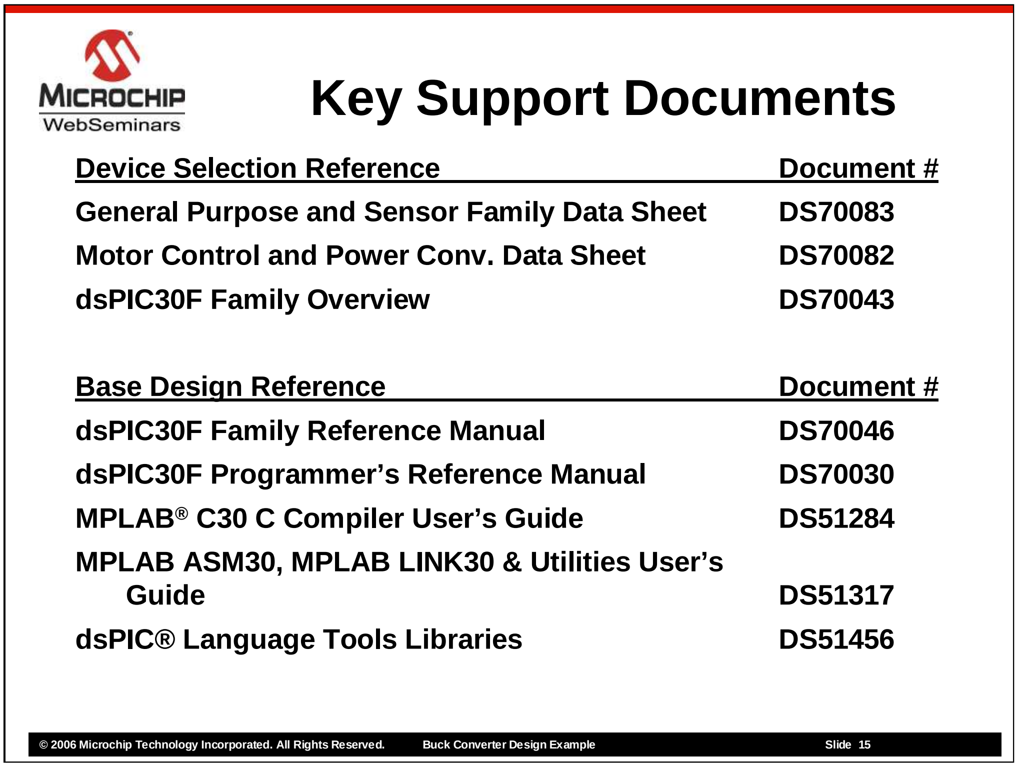
The MOSFET Q2 is clamped by a Schottky rectifier. The schottky rectifier prevents the MOSFET’s intrinsic body diode from conducting which prevents the body diode from developing a stored charge. The body diode in a MOSFET is a slow rectifier and would add significant losses if it were allowed to switch.

Because the MOSFET rectifier (synchronous rectifier) switches with less than a volt across itself, the switching losses are almost zero.

The MOSFET conduction losses are very low compared to the schottky rectifier's forward voltage drop.

The cost of the MOSFET chosen as the synchronous rectifier is about 11¢.

Synchronous Rectification can increase a power converter’s efficiency significantly and for minimal cost.



Key Support Documents

Device Selection Reference	Document #
General Purpose and Sensor Family Data Sheet	DS70083
Motor Control and Power Conv. Data Sheet	DS70082
dsPIC30F Family Overview	DS70043

Base Design Reference	Document #
dsPIC30F Family Reference Manual	DS70046
dsPIC30F Programmer’s Reference Manual	DS70030
MPLAB® C30 C Compiler User’s Guide	DS51284
MPLAB ASM30, MPLAB LINK30 & Utilities User’s Guide	DS51317
dsPIC® Language Tools Libraries	DS51456

For more information, here are references to some important documents that contain a lot of information about the dsPIC30F family of devices.

The Family Reference Manual contains detailed information about the architecture and peripherals, whereas the Programmer’s Reference Manual contains a thorough description of the instruction set.

Key Support Documents

Microchip Web Sites: www.microchip.com/smps
www.microchip.com/16-bit

For device data sheets, Family Reference Manuals, and other related documents please visit the following Microchip websites.

Thank You

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