LLC Resonant Converter Reference Design using the dsPIC® DSC

Hello, and welcome to this web seminar on Microchip's LLC Resonant Converter Reference Design. My name is Alex Dumais, and I am a Senior Applications Engineer in the High performance Microcontroller Division of Microchip.

MICROCHIP WebSeminars

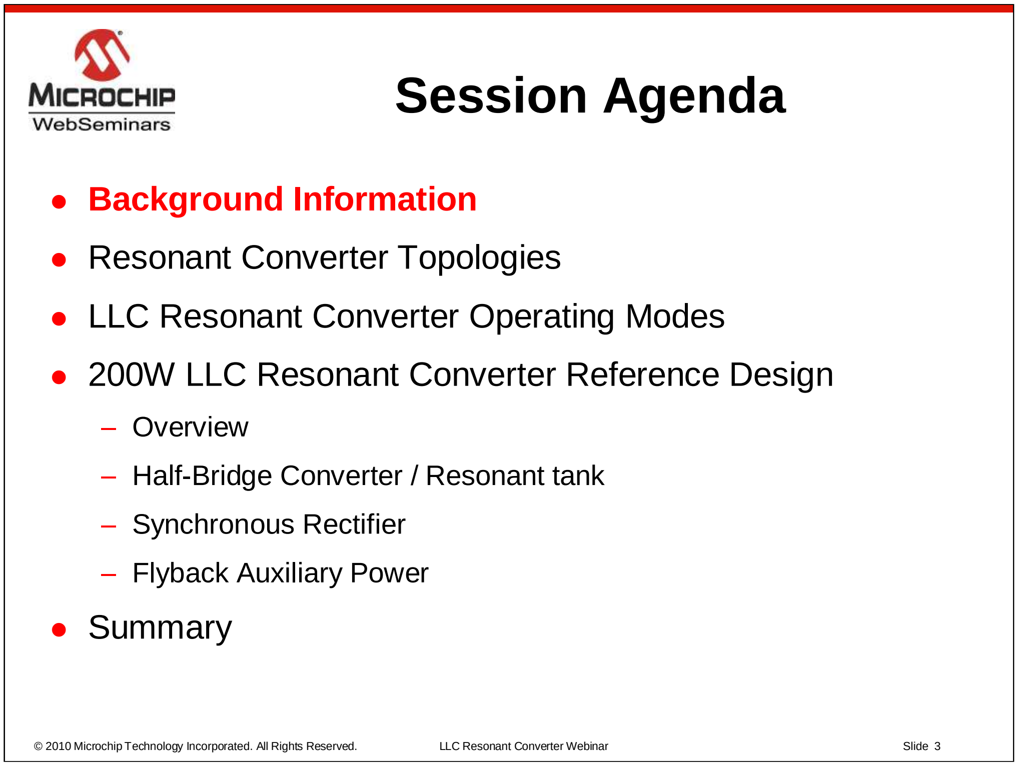
Session Agenda

- Background Information
- Resonant Converter Topologies
- LLC Resonant Converter Operating Modes
- 200W LLC Resonant Converter Reference Design
  - Overview
  - Half-Bridge Converter / Resonant tank
  - Synchronous Rectifier
  - Flyback Auxiliary Power
- Summary

 LLC Resonant Converter Webinar Slide 2

In this webinar, we will start with some background information on resonant converters and why resonant converters are gaining interest. Then we will discuss different resonant converter topologies with an emphasis on LLC resonant converters. Afterwards we will go through the design of Microchip's 200W LLC Resonant Converter Reference Design.

So let's get started with some background information on resonant converters.



In this webinar, we will start with some background information on resonant converters and why resonant converters are gaining interest. Then we will discuss different resonant converter topologies with an emphasis on LLC resonant converters. Afterwards we will go through the design of Microchip's 200W LLC Resonant Converter Reference Design.

So let's get started with some background information on resonant converters.

Why Resonant Converters

 LLC Resonant Converter Webinar Slide 4

With the push for higher efficiency converters, power supply designers are looking for different topologies to improve their power supply efficiency.

One such topology that has been gaining interest is the resonant converter. Until recently, resonant converters have been overlooked due to the complexity of control. The dsPIC digital signal controller with its advanced peripherals and high-speed DSP engine provides the capability to easily control complex systems such as Resonant Converters.

Why Resonant Converters

- High Efficiency

 LLC Resonant Converter Webinar Slide 5

Resonant converters are becoming more and more popular these days due to their ability to achieve high efficiency through softly commutating the switching devices.

MICROCHIP WebSeminars

Why Resonant Converters

- High Efficiency
- Soft-Switching Converters

 LLC Resonant Converter Webinar Slide 6

Soft-switching techniques, such as Zero-Voltage Switching and Zero-Current Switching can be implemented which provides better EMI performance along with higher efficiency

Microchip WebSeminars

Why Resonant Converters

- High Efficiency
- Soft-Switching Converters
- Higher Power Density

 LLC Resonant Converter Webinar Slide 7

Resonant Converters are capable of achieving higher power density meaning the overall converter size can be reduced as the converter can operate at higher switching frequencies due to soft-switching described above

Why Resonant Converters

- High Efficiency
- Soft-Switching Converters
- Higher Power Density
- High Power Applications

 LLC Resonant Converter Webinar Slide 8

Resonant Converters are well suited for high power applications

Why Resonant Converters

- High Efficiency
- Soft-Switching Converters
- Higher Power Density
- High Power Applications
- Wide Input Voltage Range

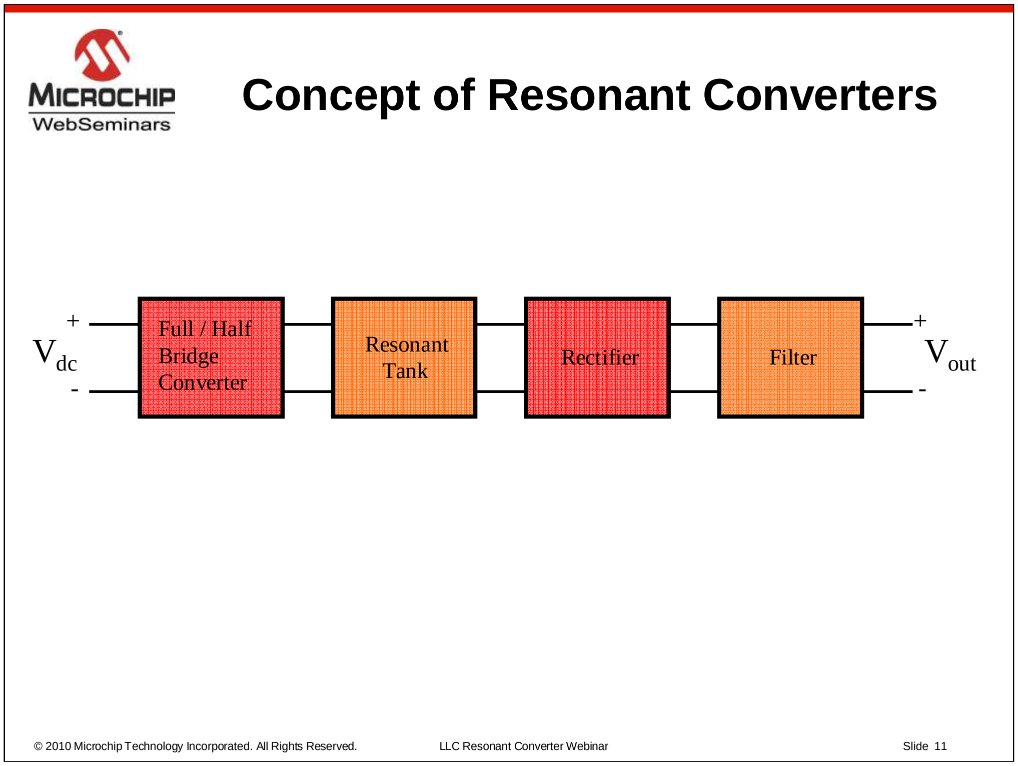
They work well over a wide input voltage range

MICROCHIP
WebSeminars

Why Resonant Converters

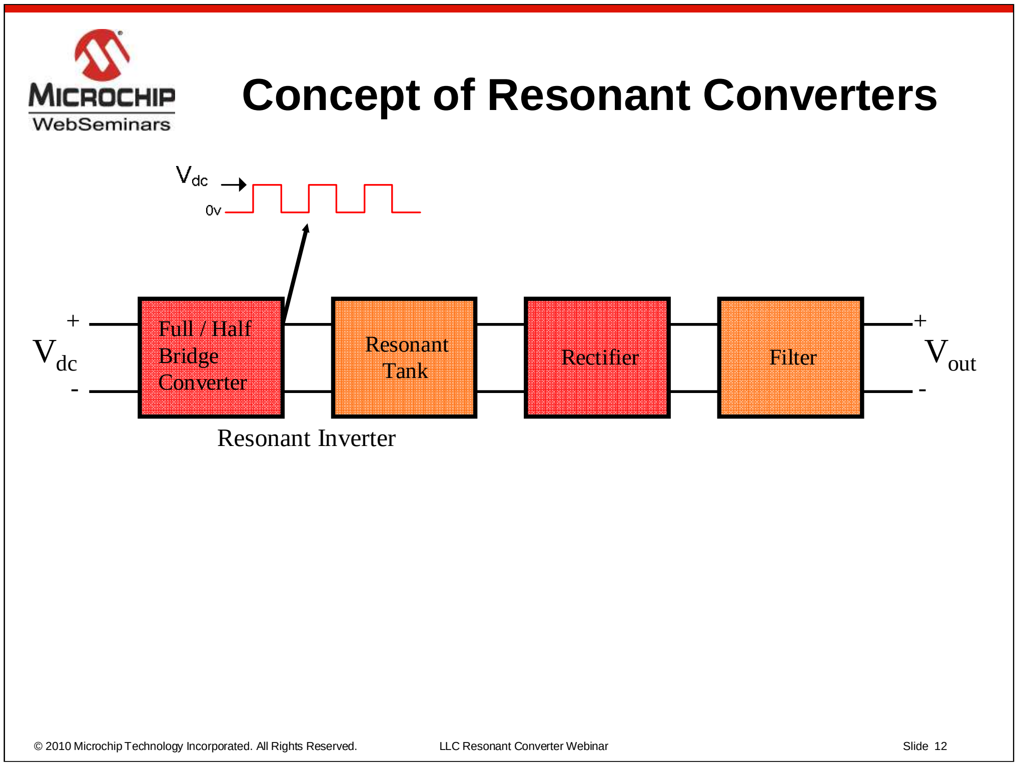
- High Efficiency
- Soft-Switching Converters
- Higher Power Density
- High Power Applications
- Wide Input Voltage Range
- Lower Cost

Lower cost – Due to their Higher switching frequencies the size of passive components can be reduced

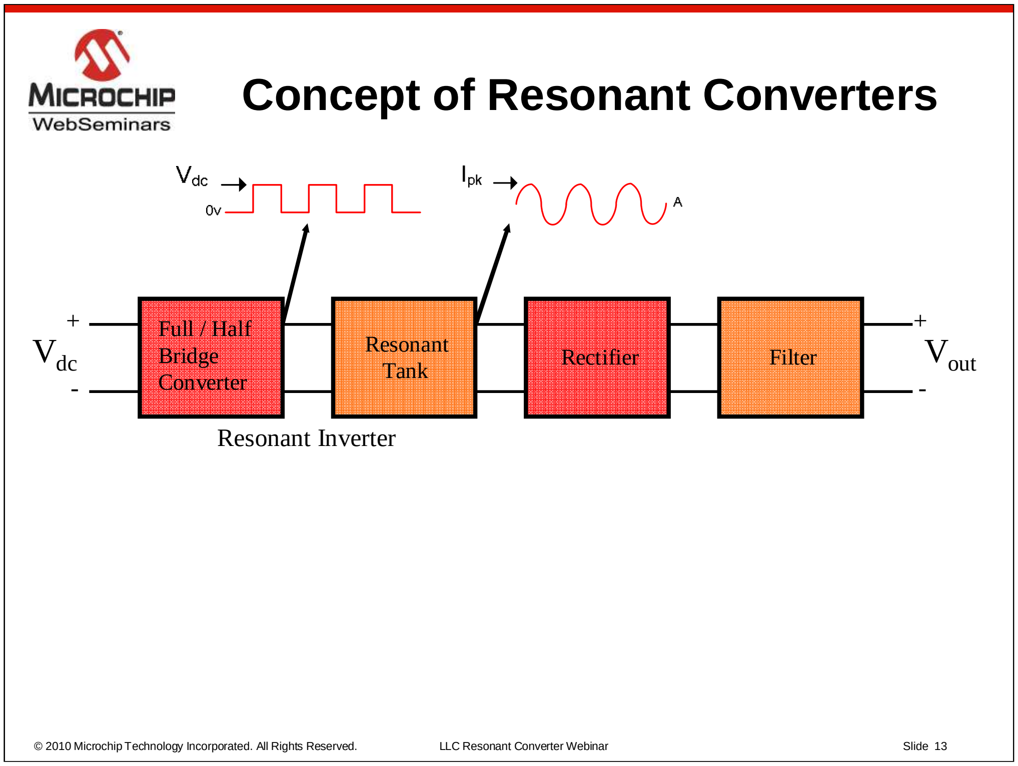


This slide demonstrates at high-level, the architecture of any resonant converter. A resonant converter can be divided into four main block sets: the full/half Bridge Converter, a Resonant Tank, a Rectifier, and a low-pass filter.

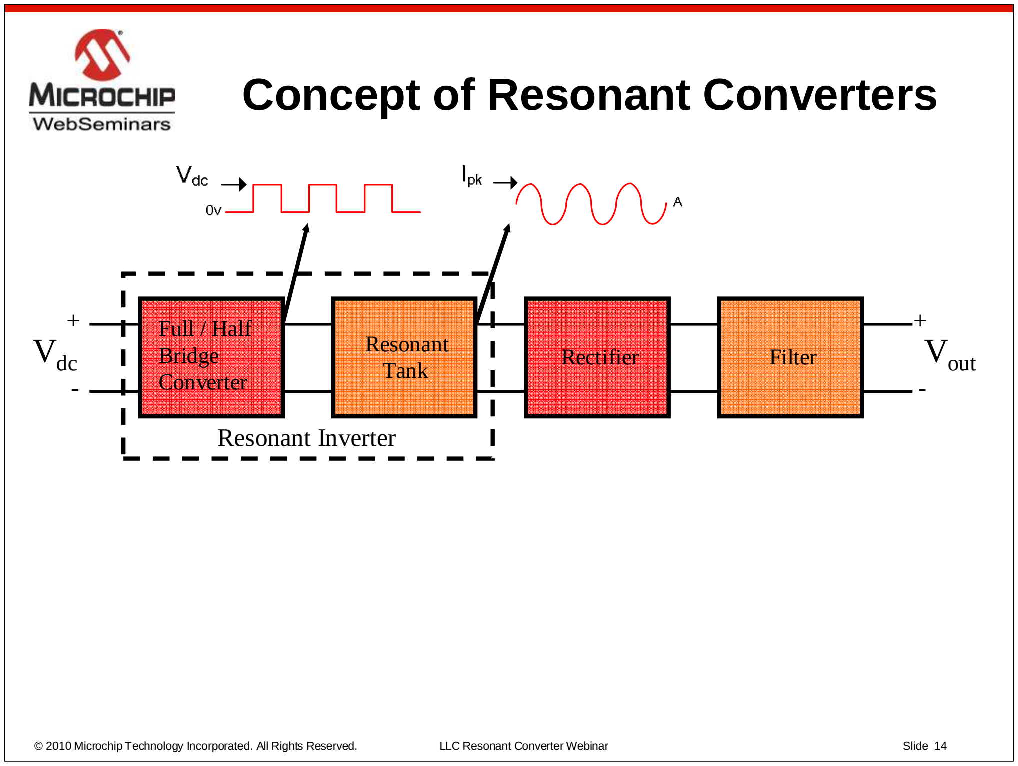
Starting on the input side the full/half bridge converter is typically configured in complementary mode with a fixed duty cycle (~50%) and with some dead-time. The bridge converter is typically operated by adjusting the duty cycle but in the case of the resonant converter the bridge converter is frequency controlled. This means that by changing the frequency of the converter we change the impedance of the resonant tank. We will discuss more on this at a later time.



The output of the bridge converter is a square wave with fixed duty cycle, with an amplitude equal to Vdc and a DC offset of Vdc/2.



The resonant tank is made up of reactive components (capacitors and inductors) and can have several different configurations. Depending on the tank configuration, the output will have either a sinusoidal current or voltage. The resonant tank will introduce a phase shift between the voltage and current and because of this we are able to achieve soft-switching.

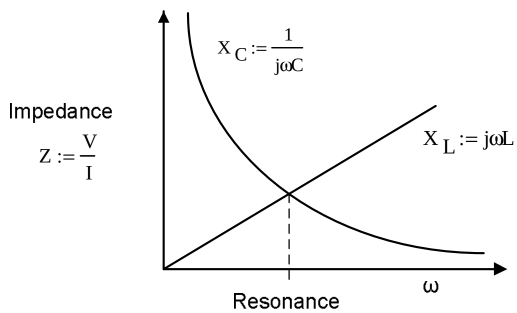


Combining the bridge converter and the resonant tank we create a resonant inverter and by adding a rectifier and low pass filter we create a resonant converter.

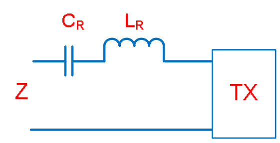
MICROCHIP WebSeminars

What is Resonance

- Resonance occurs in a circuit at a particular frequency where the impedance between the input and output of the circuit is at its minimum.



At a particular frequency two Reactance's will be equal in magnitude but opposite in sign $X_L = - X_C$



 LLC Resonant Converter Webinar Slide 15

Before we dive any deeper into resonant converters we should first understand a couple terms that are commonly used in describing resonant converters.

So first let us look at the meaning of resonance.

In a simple series LC circuit (shown in bottom right) there exist a point where the reactance of the capacitor and the reactance of the inductor are equal in magnitude but opposite in sign. At this particular frequency the reactance is zero and the impedance between the input and the output of the circuit is at it's minimum.

If we look at the impedance vs. frequency plot we will see that the summation of the capacitor and inductor reactance is at it's minimum at the resonant point.

Quality Factor

- Quality Factor (Q), of a resonant circuit is a dimensionless parameter that describes how damped a resonant circuit is.
- The higher the Quality Factor the more narrow the bandwidth.
- Q is the ratio between the power stored and the power dissipated in the circuit.

General Definition:

$$Q = P_{stored} / P_{dissipated} = I^2X / I^2R$$

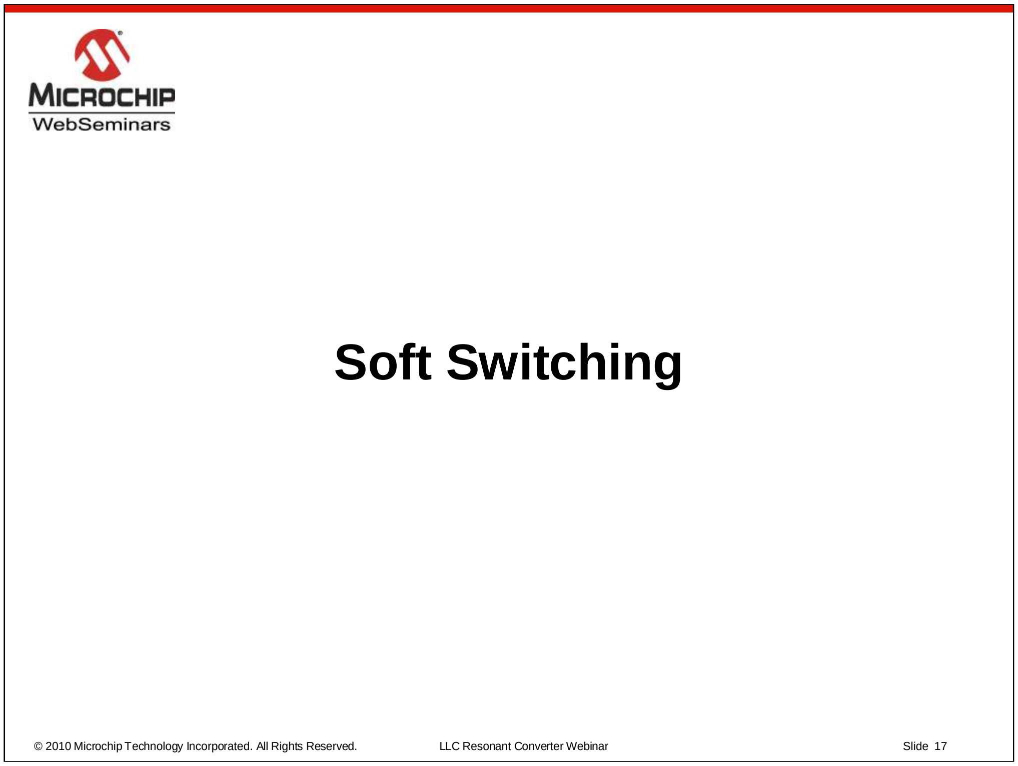
Another term used to describe resonant converters is Quality Factor.

Quality Factor (Q) is a dimensionless parameter that describes how damped a resonant circuit is.

The higher the Quality Factor the narrower the bandwidth of the system.

As a general definition Quality Factor can be defined as the ratio between the power stored and the power dissipated in the circuit.

It is important to note that the Quality Factor changes with load, (i.e. it is not a fixed parameter).



As discussed earlier, resonant converters are able to achieve high efficiency from employing soft-switching techniques. The following slides discuss what these soft-switching techniques are and their advantages.

Zero Voltage Switching

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
  - ZVS demonstrated only at Switch turn-ON

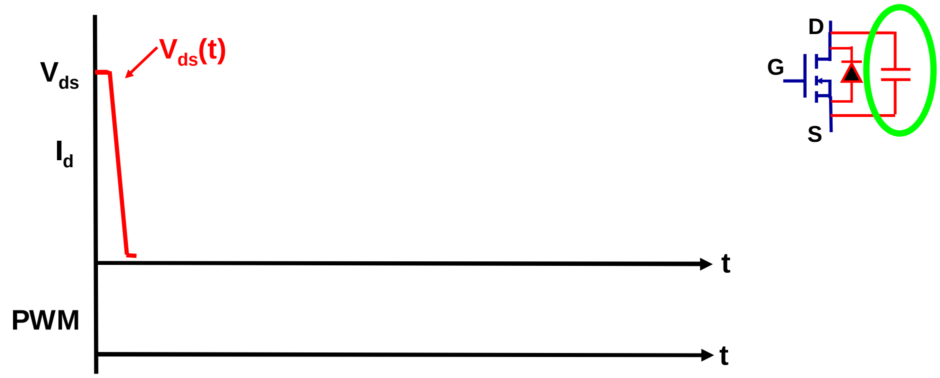
 LLC Resonant Converter Webinar Slide 18

The following animation demonstrates Zero Voltage Switching.

Zero Voltage Switching

MICROCHIP WebSeminars

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
  - ZVS demonstrated only at Switch turn-ON



 LLC Resonant Converter Webinar Slide 19

First the drain-to-source capacitance of the MOSFET is discharged.

MICROCHIP WebSeminars

Zero Voltage Switching

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
    - ZVS demonstrated only at Switch turn-ON

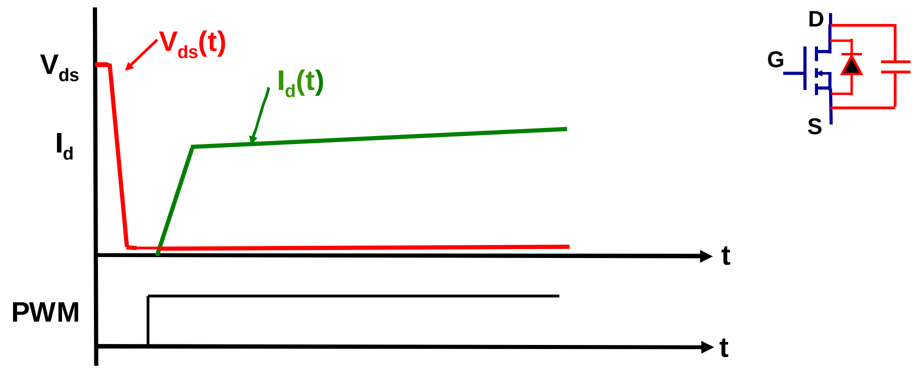
 LLC Resonant Converter Webinar Slide 20

Next the PWM enables the MOSFET allowing the current through the MOSFET to begin to rise

Zero Voltage Switching

MICROCHIP WebSeminars

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
  - ZVS demonstrated only at Switch turn-ON



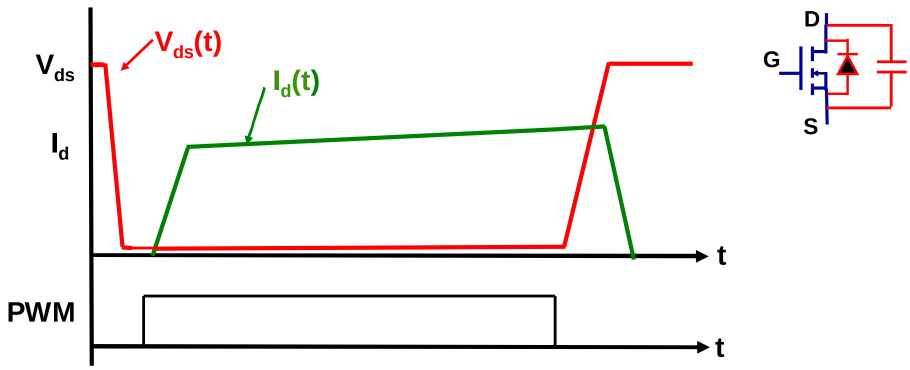
 LLC Resonant Converter Webinar Slide 21

When the PWM is disabled the drain-to-source voltage begins to rise but the current still flows through the MOSFET.

Zero Voltage Switching

MICROCHIP WebSeminars

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
  - ZVS demonstrated only at Switch turn-ON



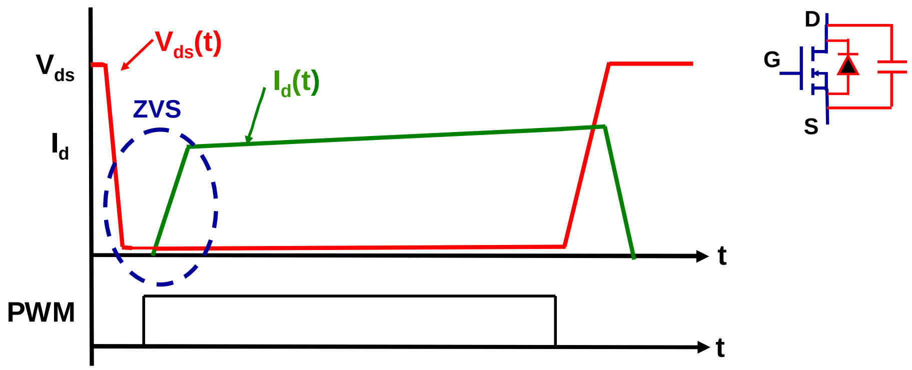
 LLC Resonant Converter Webinar Slide 22

When the PWM is disabled the drain-to-source voltage begins to rise but the current still flows through the MOSFET.

MICROCHIP WebSeminars

Zero Voltage Switching

- At transition period from one state to another state of the MOSFET, the voltage is zero, hence no losses
    - ZVS demonstrated only at Switch turn-ON

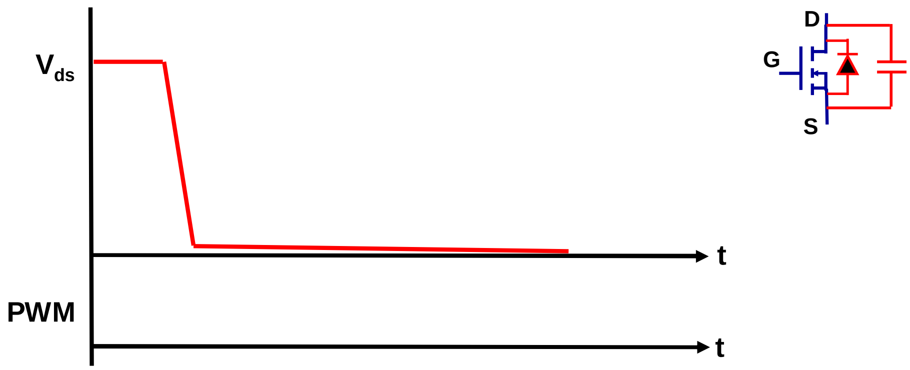


From this animation we can see that at switch turn-on we are eliminating the MOSFET switching losses as the voltage across the drain-to-source is zero (ZVS). At switch turn-off we see that there will be a significant amount of current and voltage at the transition state which translates into switching losses.

Zero Voltage switching is preferred in high-voltage, high-power applications.

Zero Current Switching

- At transition period from one state to another state of the MOSFET, current is zero, hence no losses
  - ZCS demonstrated only at Switch Turn-OFF

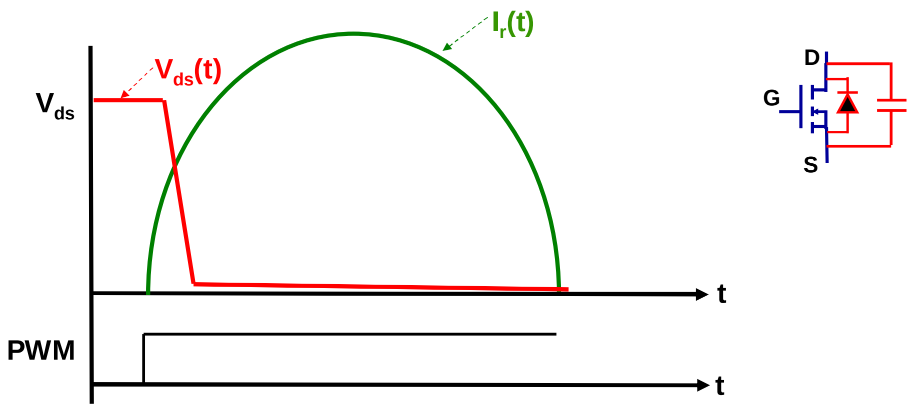


 LLC Resonant Converter Webinar Slide 24

The following animation demonstrates Zero Current Switching.

Zero Current Switching

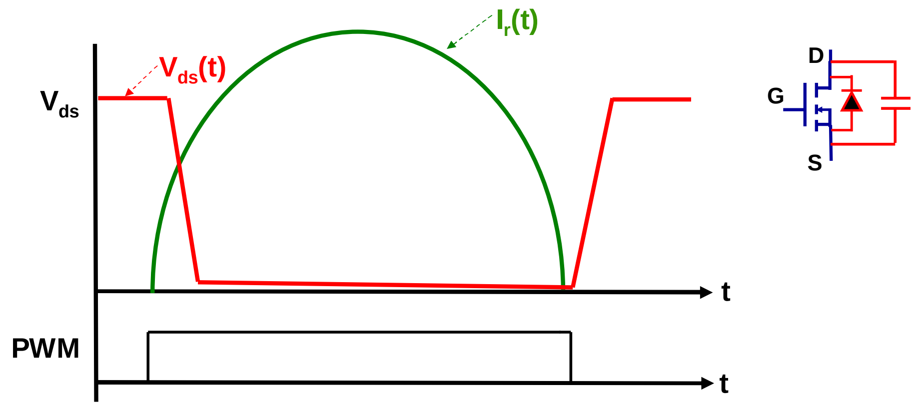
- At transition period from one state to another state of the MOSFET, current is zero, hence no losses
  - ZCS demonstrated only at Switch Turn-OFF



First the PWM is enabled and the current through the MOSFET begins to rise as the MOSFETs drain-to-source voltage drops.

Zero Current Switching

- At transition period from one state to another state of the MOSFET, current is zero, hence no losses
  - ZCS demonstrated only at Switch Turn-OFF

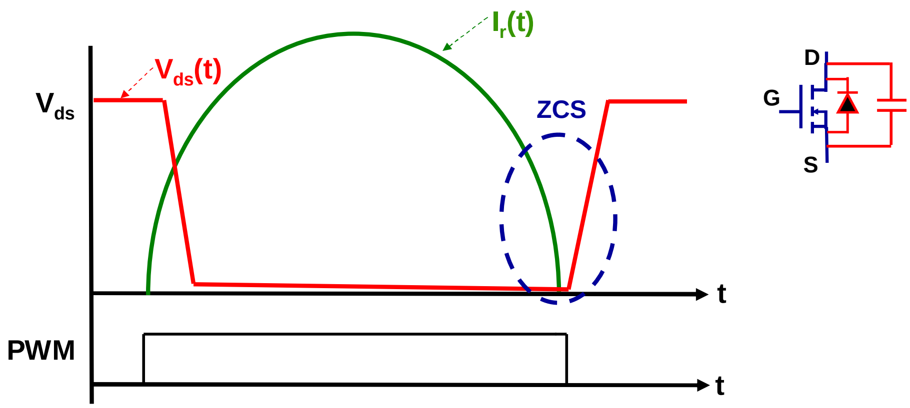


 LLC Resonant Converter Webinar Slide 26

Once the current through the MOSFET becomes zero, we disable the MOSFET. Now the drain-to-source voltage begins to rise.

Zero Current Switching

- At transition period from one state to another state of the MOSFET, current is zero, hence no losses
  - ZCS demonstrated only at Switch Turn-OFF



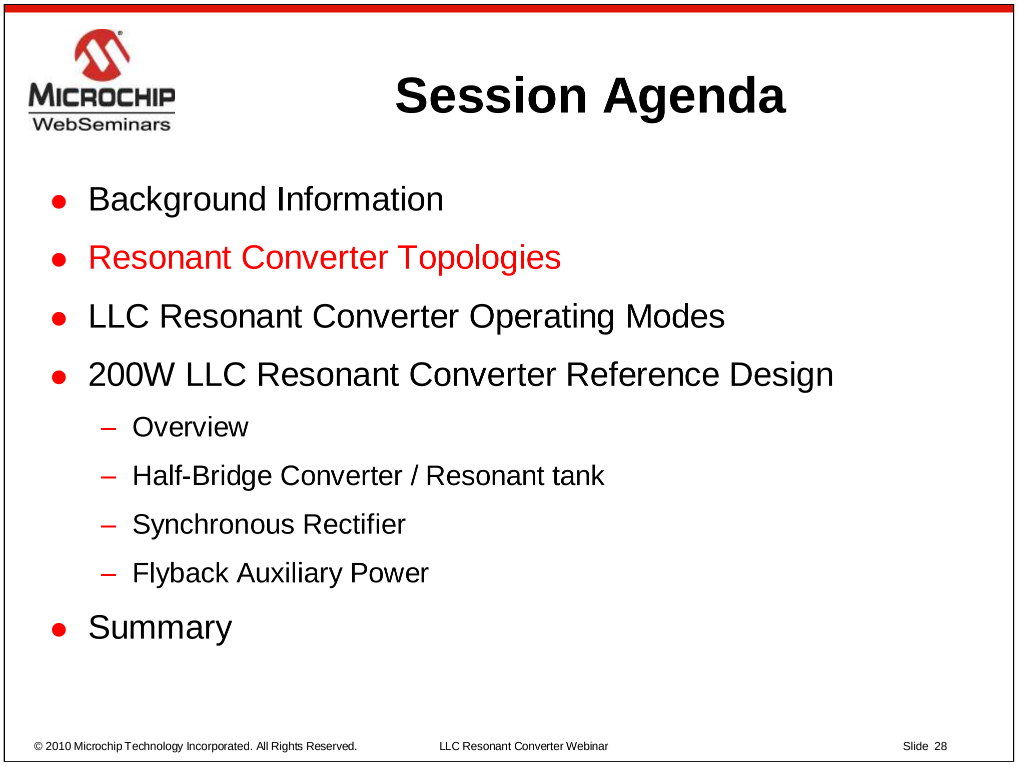
 LLC Resonant Converter Webinar Slide 27

This is the point at which zero current switching occurs

From the animation we can see that at switch turn-off we are eliminating the MOSFET switching losses as the current is zero and the drain-to-source voltage is also zero. At switch turn-on we see that there will be a significant amount of current and voltage at the transition state which translates into switching losses.

Zero Current switching can be implemented at switch turn-on as well as turn-off.

With soft-switching we can reduce the noise in the system, therefore improving EMI performance.

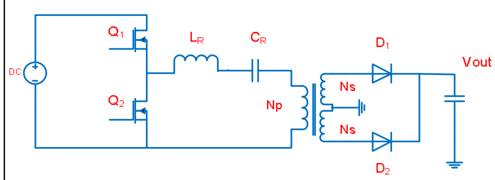


Next we will take a closer look at three different resonant converter topologies.

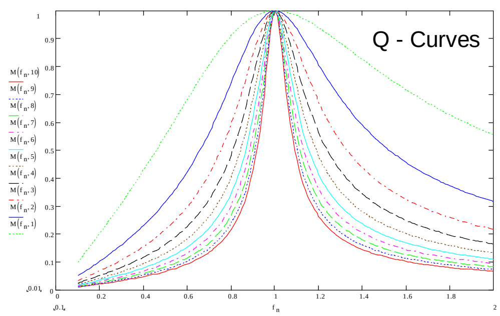
MICROCHIP WebSeminars

Series Resonant Converter

- Resonant tank (L_R & C_R) is in series with the output load
- Resonant tank and the load act as a voltage divider (M <= 1)
- SRC can work at no load but output voltage can not be regulated
- For ZVS, need to operate above resonance (negative slope)
- At low line SRC operates closer to resonant frequency



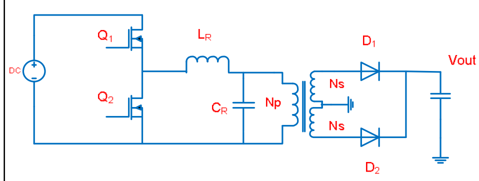
$$f_r := \frac{1}{2\pi \cdot \sqrt{L_r \cdot C_r}}$$



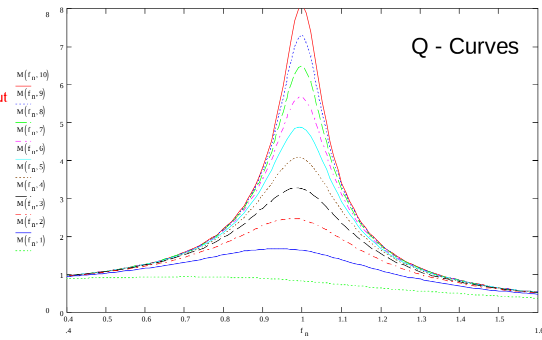
For a series resonant converter the resonant tank is composed of inductor Lr and capacitor Cr in a series configuration (shown in schematic). It is called a series resonant converter because the resonant tank is in series with the output load. Here the resonant tank and the output load act as a voltage divider and therefore limiting the gain of the tank to be less then or equal to one. Looking at the Voltage gain curves (bottom right diagram) we see that all Q-curves intersect at the resonant frequency point (Fn = 1, and Gain = 1). From the voltage gain plot we can also see that the converter operates closer to resonance when the input voltage is at low line. For Zero Voltage Switching the converter must work at or above resonance.

Parallel Resonant Converter

- Load is in parallel with resonant capacitor
- PRC can operate at no load
- For ZVS, need to operate above resonance (negative slope)
- At low line PRC operates closer to resonant frequency
- High circulating currents
- Inherently short circuit protected



$$f_r := \frac{1}{2\pi\cdot\sqrt{L_r \cdot C_r}}$$

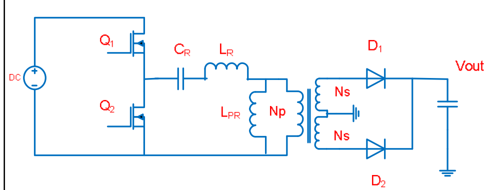


 LLC Resonant Converter Webinar Slide 30

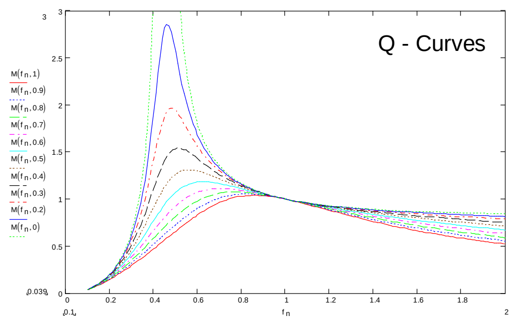
For a parallel resonant converter, the resonant tank is similar to that of the series resonant converter but now the output load is connected in parallel with the resonant capacitor Cr. Similar to the series resonant converter, the parallel resonant converter will operate closer to resonant frequency at low-line, and for Zero-Voltage switching the converter should work at or above resonance. Unlike the series resonant converter, the parallel resonant converter can operate at no load. One disadvantage of the parallel resonant converter is that is will operate with high circulating currents, even at no load conditions.

Series-Parallel Resonant Converter - LLC

- Can operate at resonance at nominal input voltage
- The LLC converter is able to operate at no load
- Can be designed to operate over a wide input voltage
- Zero voltage switching is achievable over the entire operating range
- Zero current switching is achievable over the entire operating range



$$f_r := \frac{1}{2\pi\cdot\sqrt{L_r \cdot C_r}} \qquad f_{r2} := \frac{1}{2\pi\cdot\sqrt{(L_r + L_{pr})\cdot C_r}}$$



 LLC Resonant Converter Webinar Slide 31

Series-parallel converters are a combination of the series resonant converter and the parallel resonant converter. Here we are showing an LLC resonant converter which is composed of two inductors and a single resonant capacitor. Another common Series-Parallel resonant converter is the LCC converter which replaces the inductor Lpr with another capacitor as in the parallel resonant configuration.

LLC resonant converters have many advantages:

•They can operate at resonance at nominal input voltage

•They can operate at no load conditions

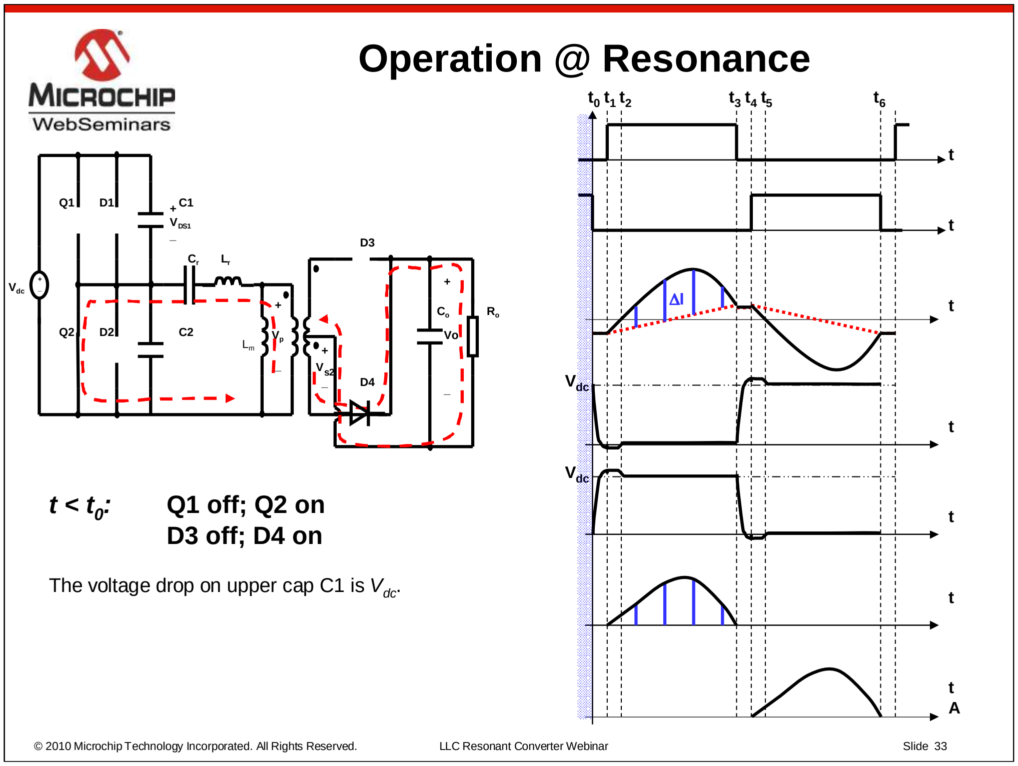
•Have lower circulating currents then the parallel resonant converter

The advantages of resonant converters are their ability to operate over a wide input voltage range and the fact that ZVS/ZCS is achievable over the entire operating condition.

Session Agenda

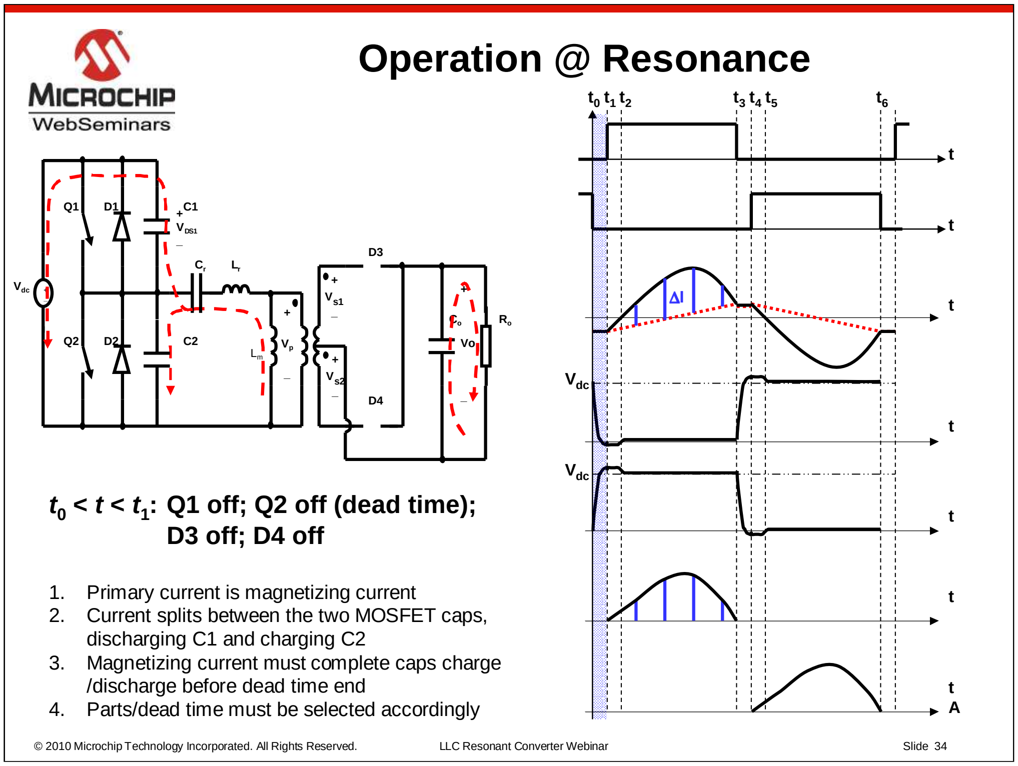
- Background Information
- Resonant Converter Topologies
- LLC Resonant Converter Operating Modes
- 200W LLC Resonant Converter Reference Design
  - Overview
  - Half-Bridge Converter / Resonant tank
  - Synchronous Rectifier
  - Flyback Auxiliary Power
- Summary

Next we will examine the different operating modes of an LLC Resonant Converter.



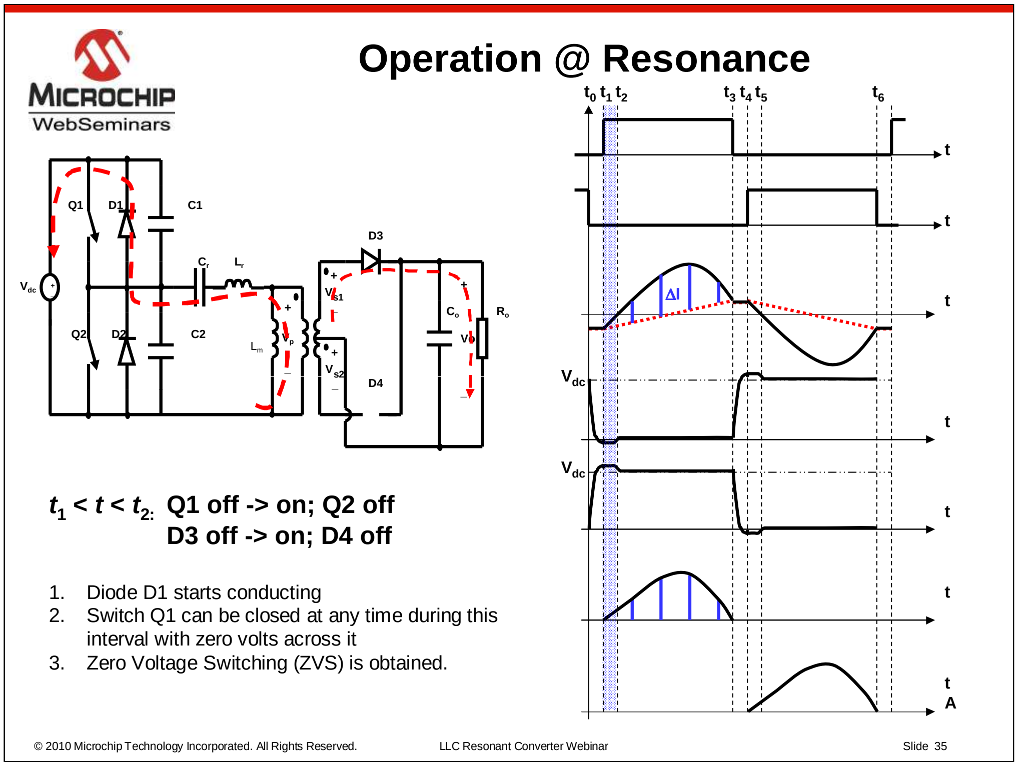
First we will start out by examining, in detail, the operational waveforms when the system operates at resonant frequency. For simplicity we are showing a half-bridge converter on the primary side and a full-wave rectifier on the secondary. Diodes D1,D2 and Capacitors C1, C2 have been explicitly drawn here but are essentially part of the MOSFETs parasitics.

At time t<t0, the bottom MOSFET (Q2) is conducting and diode (D4) is forward biased. The voltage drop across capacitor C1 is equal to the input voltage (Vdc).



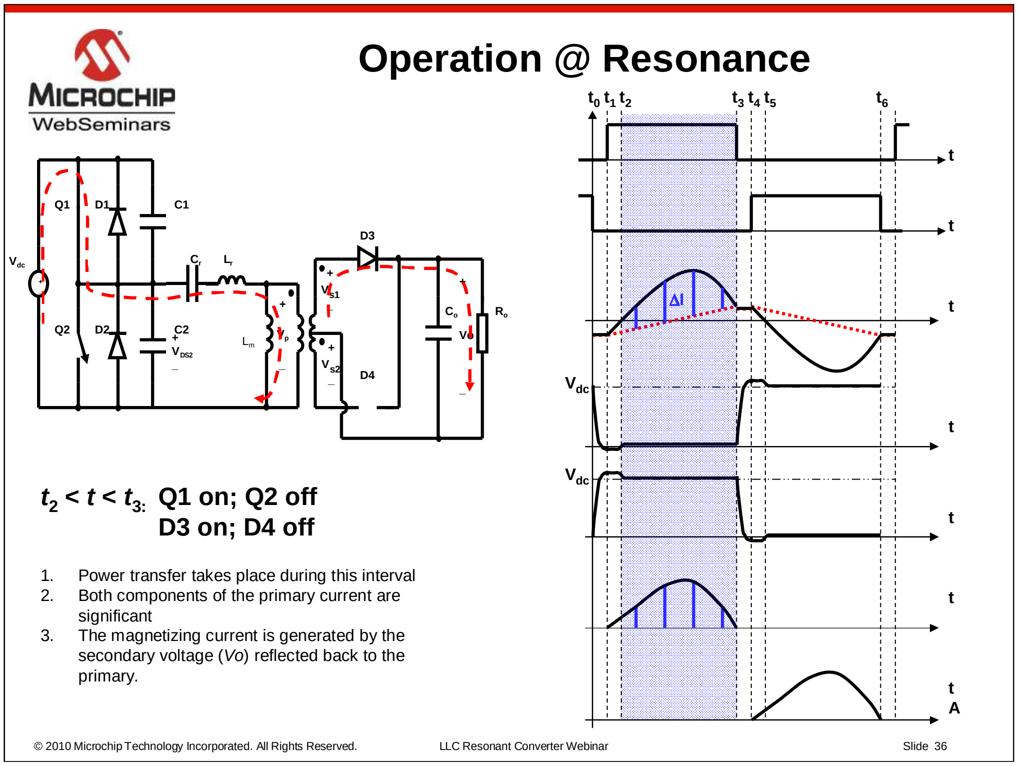
At time t0<t<t1, both MOSFETs are disabled (known as dead-time region) and both secondary diodes D3, D4 are reversed biased. At this time the output capacitor is supplying the required load current.

On the primary side we see that the magnetizing current is flowing and will begin to discharge capacitor C1 and charge capacitor C2. The magnetizing current must be large enough to charge/discharge the capacitors before the dead-time interval ends.



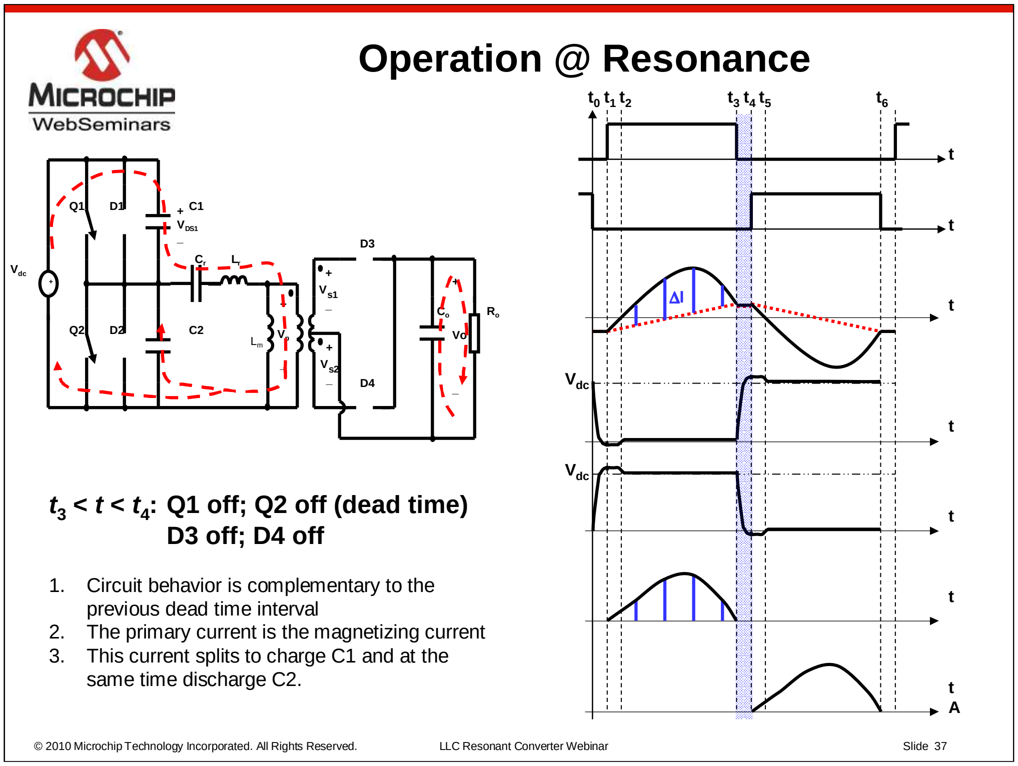
At the time interval t1<t<t2, the high side MOSFET (Q1) begins to transition to the on-state. Initially the magnetizing current is negative and the internal body diode of the MOSFET will be forward biased. Diode D3 is also transitioning to forward biased.

When MOSFET (Q1) is enabled, the drain to source voltage is zero, therefore Zero Voltage Switching is obtained.



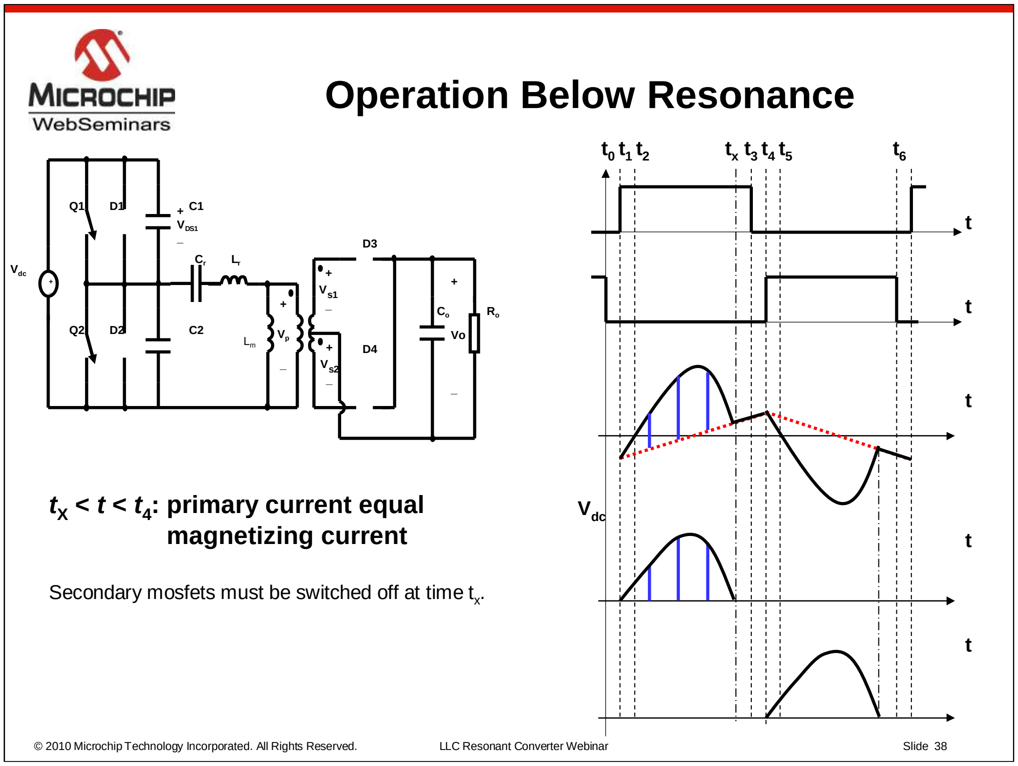
At time t2<t<t3, both MOSFET Q1 and Diode D3 are conducting. This is the first interval in which power transfer takes place. The tank current is supplied by the input voltage source and the magnetizing current is generated by the secondary voltage reflected back to the primary by the transformer turns ratio. The magnetizing inductor is clamped at this voltage, hence the linear rise of magnetizing current.

The sinusoidal tank current flowing in the transformer will generate a quasi-sinusoidal current on the secondary side related by the transformer turns ratio. At the end of the switching cycle the current flowing through diode D3 will be equal to zero, hence zero current switching is achieved on the secondary.



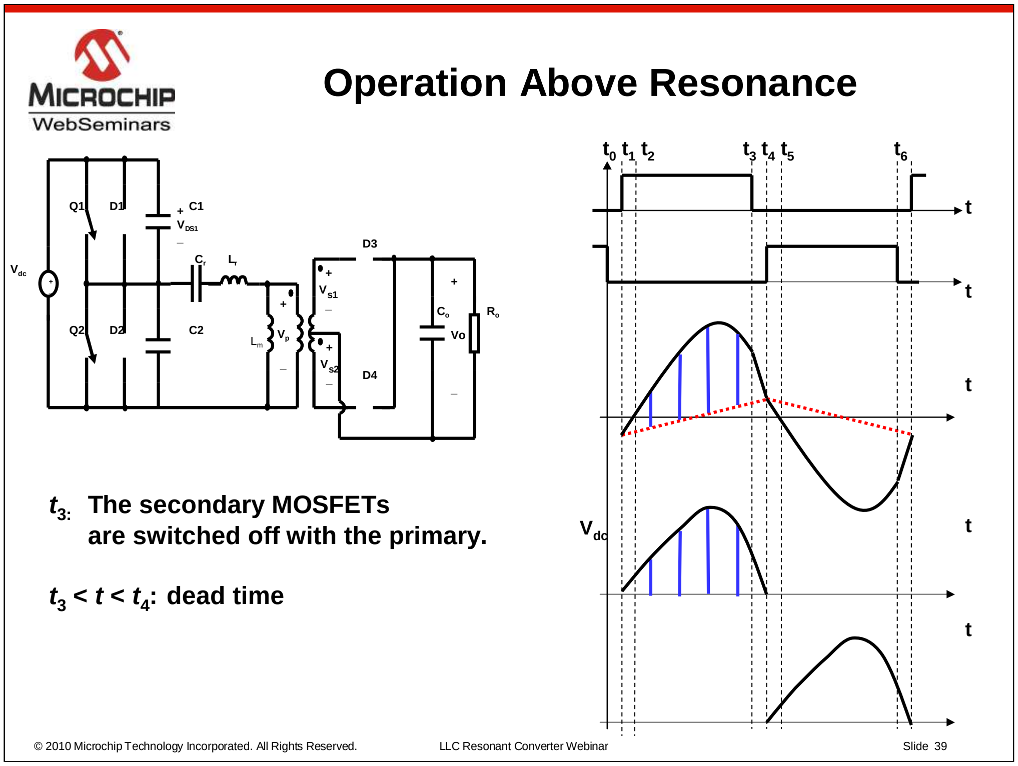
At the time interval t3<t<t4, the primary current is the magnetizing current. The circuit operation is the same as the previous dead-time interval except now, capacitor C1 is being charged while capacitor C2 is discharged.

The circuit operation for the remaining time intervals will be the reverse of the first half cycle.



Now that we have reviewed in detail the circuit operation at resonance, we will review the differences in circuit behavior when the converter operates above and below resonance.

When operating below resonance the tank fundamental sine wave will have a shorter period then that of the switching frequency (decreasing the switching frequency = an increase in the switching period). From the figure we can see that the tank current will equal the magnetizing current before the half period ends (tx – t3). From this point on the current flowing in the primary is that of the magnetizing current.



The circuit behavior is somehow reversed compared to the operation below resonance.

Since the resonant period is longer then that of the switching period, at the end of the switching half period, the tank current is higher than the magnetizing current. During the dead time interval the tank current falls rapidly to the value of the magnetizing current, so that a new half cycle can start.

Session Agenda

MICROCHIP WebSeminars

- Background Information
- Resonant Converter Topologies
- LLC Resonant Converter Operating Modes
- 200W LLC Resonant Converter Reference Design
  - Overview
  - Half-Bridge Converter / Resonant tank
  - Synchronous Rectifier
  - Flyback Auxiliary Power
- Summary

Now that we have some background information on resonant converters we can proceed with looking at Microchip’s 200W LLC Resonant Converter Reference Design.

LLC Resonant Converter Reference Design Specifications

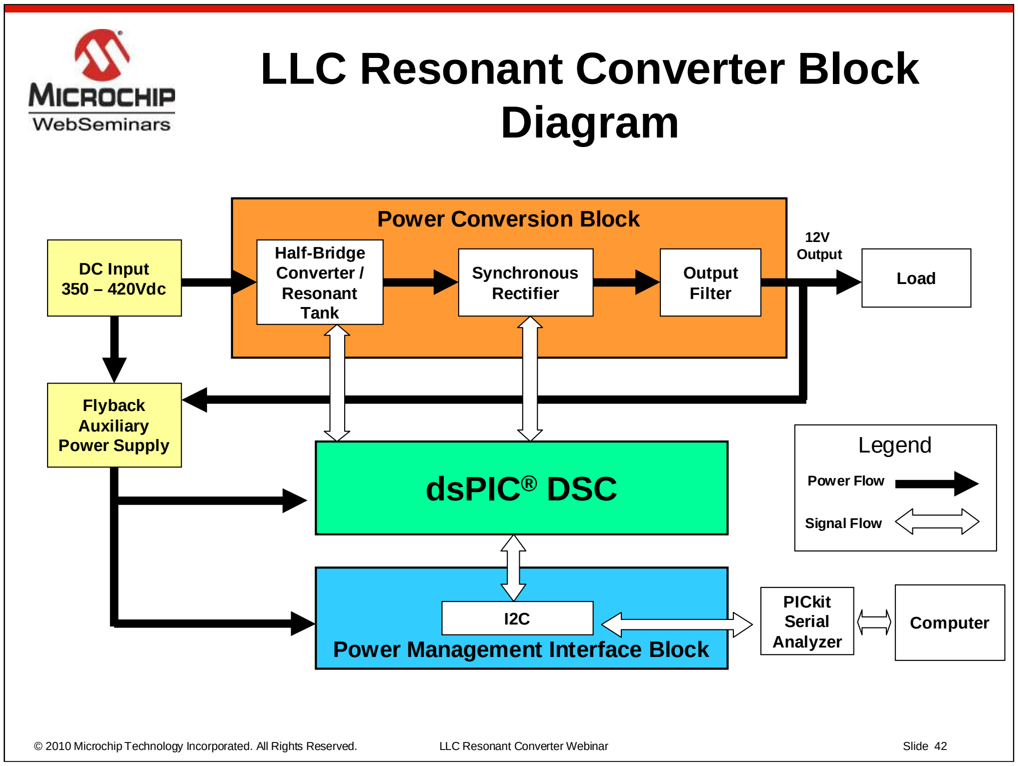
- **Input Range:**
  - **350Vdc to 420Vdc**
  - **400Vdc nominal**
- **Output Voltage:**
  - **12Vdc**
- **Output Power:**
  - **200W**
- **High Efficiency: 95%**
- **Resonant Frequency:**
  - **200KHz**
- **Modulated Frequency:**
  - **150KHz – 220KHz**

 LLC Resonant Converter Webinar Slide 41

The LLC Resonant Converter Reference Design is rated for 200W with a nominal input voltage of 400V DC. This LLC reference design is intended to be the second stage in a AC-DC application so the nominal input voltage is the typical output voltage of a PFC converter (385 - 400V). The ability of the LLC converter to operate over a wide input range allows the bulk capacitors on the PFC converter (which are required for hold-up time) to be reduced.

As this design is 200W the half-bridge converter was selected for driving the resonant tank. As for the rectifier, the traditional full-wave rectifier was replaced with a synchronous rectifier circuit, where MOSFETs replace diodes, to improve efficiency. High-voltage isolation (~4kV) separating the primary and secondary is obtained through proper component selection and magnetic structures.

Use of the reference design is Royalty Free, and complete documentation, software, and hardware design information is available on the Microchip web site. Demonstration units are also available from worldwide Microchip sales offices.



This slide shows a system-level block diagram of the LLC Resonant Converter. A single dsPIC33F "GS" series digital signal controller, shown in the center of the block diagram, drives the power stages (Half-bridge converter and Synchronous Rectifier), performs control loop operations, power management communication and fault management routines.

LLC Resonant Converter Board Layout:

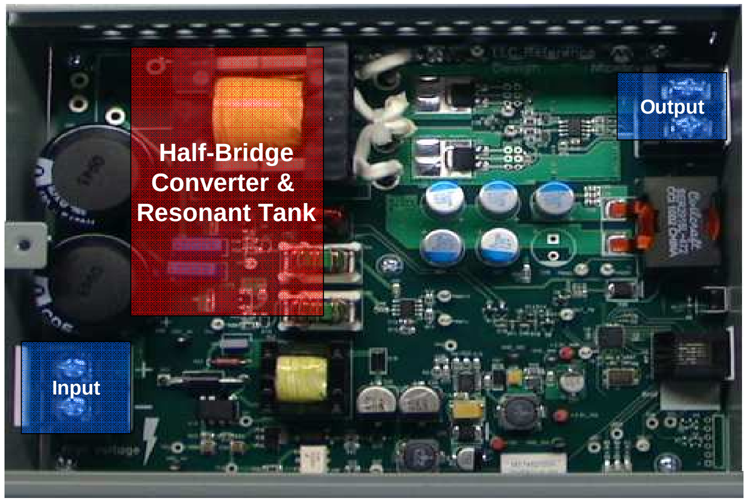
Now that we have seen a functional overview of the LLC Resonant Converter, we can physically locate all sections on a picture of the Reference Design itself.

This is a top view of the LLC Resonant Converter Reference Design. Positions of each block of the system are highlighted as follows:

LLC Resonant Converter Board Layout:

The input terminal can be seen on the bottom left and the output terminal on the top right

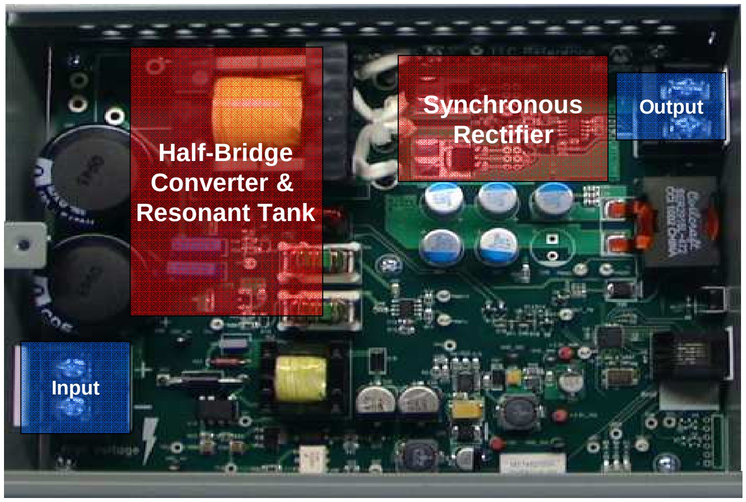
LLC Resonant Converter Board Layout:



 LLC Resonant Converter Webinar Slide 45

The Half-bridge Converter can be found towards the upper left side.

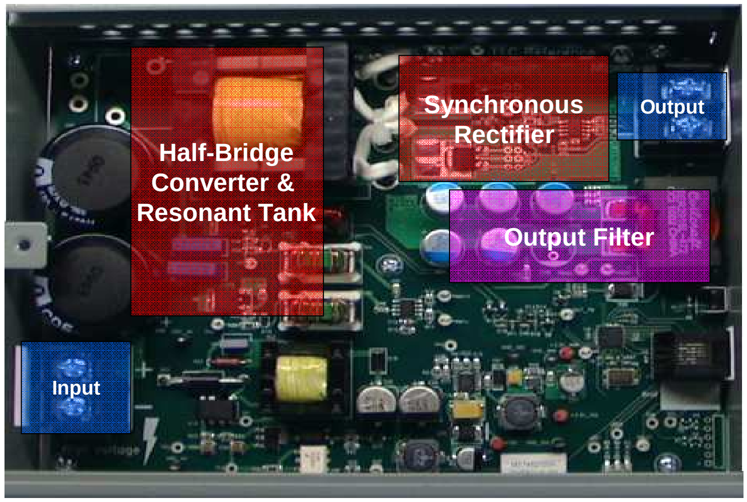
LLC Resonant Converter Board Layout:



The Synchronous Rectifier is located on the top right

MICROCHIP
WebSeminars

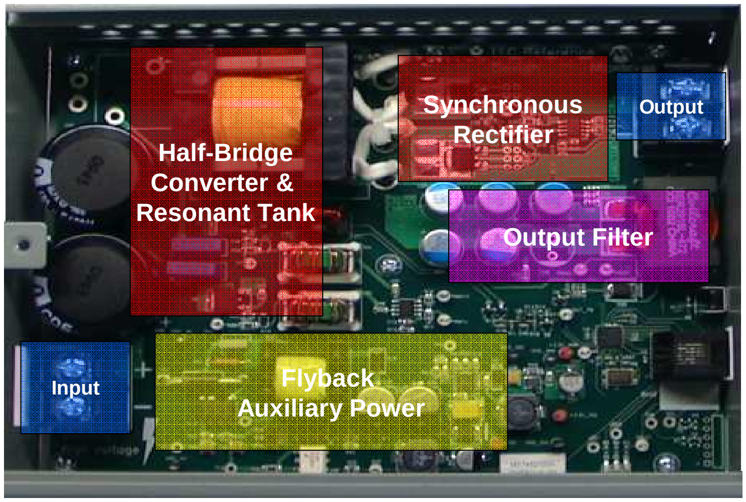
LLC Resonant Converter Board Layout:



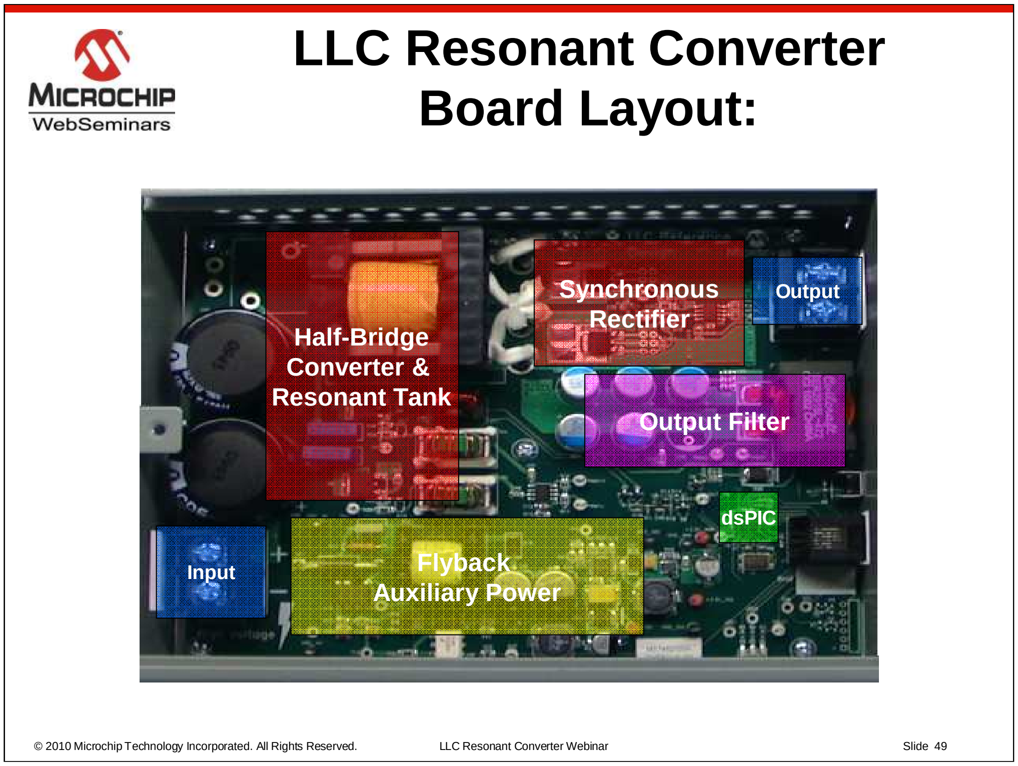
 LLC Resonant Converter Webinar Slide 47

Output Filter on the middle right hand side

LLC Resonant Converter Board Layout:



Flyback Auxiliary Power on the bottom Left



And lastly the dsPIC DSC is located on the bottom right of the board.

MICROCHIP WebSeminars

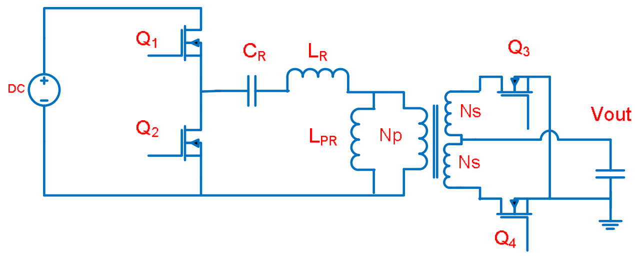
Session Agenda

- Background Information
- Resonant Converter Topologies
- LLC Resonant Converter Operating Modes
- 200W LLC Resonant Converter Reference Design
  - Overview
  - Half-Bridge Converter / Resonant tank
  - Synchronous Rectifier
  - Flyback Auxiliary Power
- Summary

 LLC Resonant Converter Webinar Slide 50

Next we will look at the operation of the half-bridge converter and the resonant tank.

Half-Bridge Converter / Resonant Tank



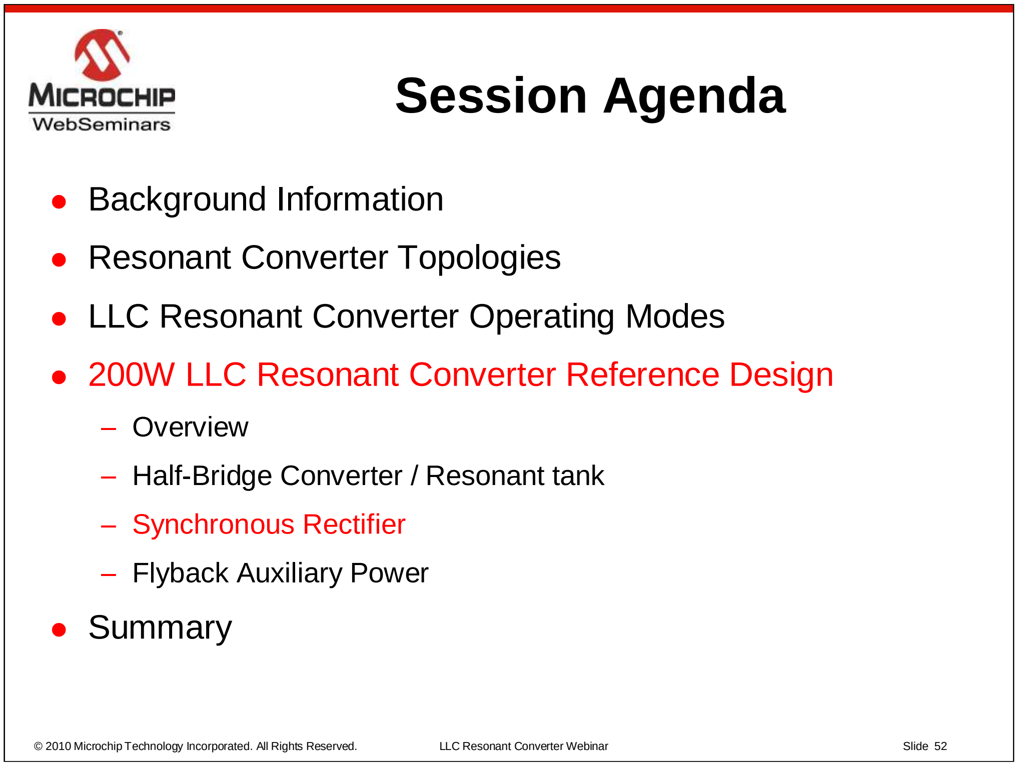
- Half-Bridge Converter generates a square wave with amplitude = V_{DC} and dc offset of $V_{DC}/2$
- Resonant capacitor C_R blocks dc component
- Resonant tank filters higher harmonics, essentially sinusoidal current is allowed to flow

A circuit diagram of the half-bridge converter and the resonant tank is as shown.

Two MOSFETs are connected in a bridge configuration and the resonant tank is connected at the Half-Bridge point. The half-bridge converter is configured in complementary mode with a fixed duty cycle (~50%) and with some dead-time The dead-time serves two purposes: first, it prevents shoot-through (both MOSFETs on at the same time), secondly, it is the time interval used to charge/discharge the MOSFETs drain-to-source capacitance used for zero voltage switching (as seen earlier in the presentation). Because of the high switching frequencies MOSFETs are preferred over IGBT's.

The resonant capacitor blocks the DC component of the square wave, producing a signal that is centered around 0v.

The resonant tank will filter the higher harmonics essentially only allowing sinusoidal current to flow.

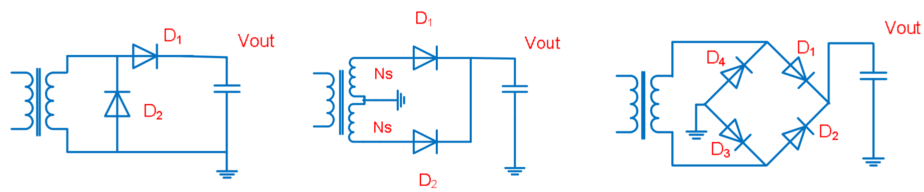


Next lets look at the rectifier block found on the secondary side.

MICROCHIP WebSeminars

Types of Rectifiers

- **Three topologies to consider:**
  - **Half-wave rectifier**
  - **Full-wave rectifier (center-tapped)**
  - **Bridge rectifier – High output voltage low output current**



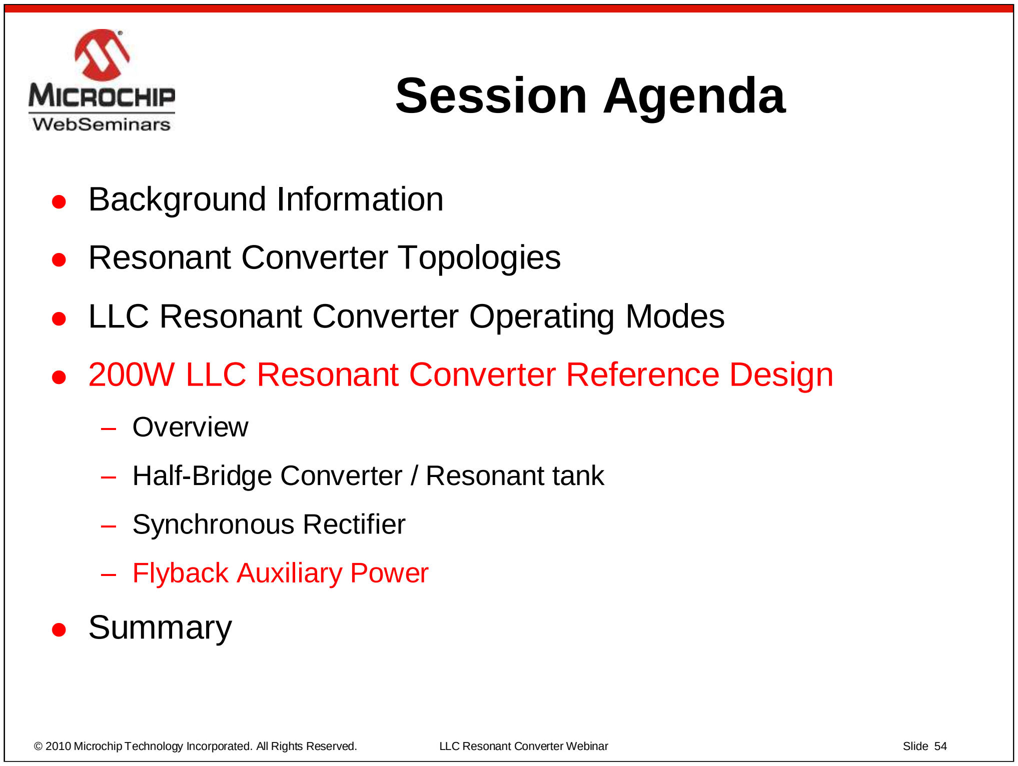
Half-wave Full-wave Bridge-Rectifier

 LLC Resonant Converter Webinar Slide 53

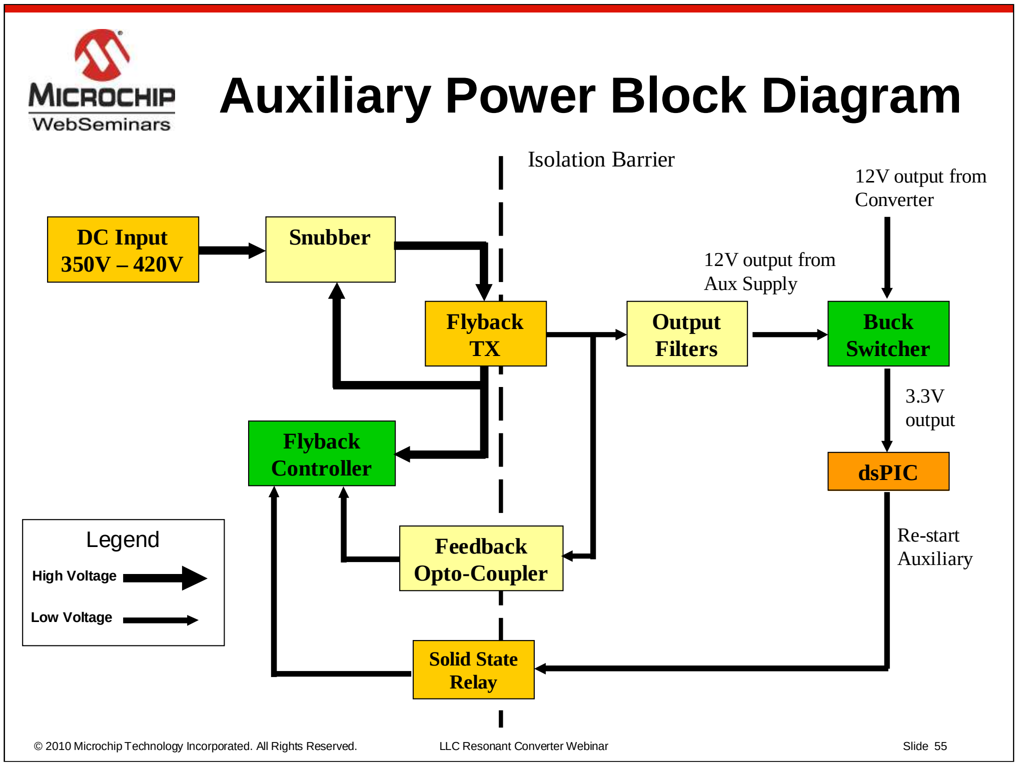
There are three different rectifier topologies to consider: Half-wave, Full-wave, and Bridge Rectifier. As this application has a low output voltage (12V) and high output current the bridge rectifier is not a suitable solution.

For this reference design we have used a Full-Wave rectifier but we have replaced the Diodes with MOSFETs. This is more commonly known as synchronous rectification. The MOSFETs switching losses and conduction losses are less then that of the Diodes losses, which helps improve overall efficiency. The MOSFETs have been placed on the low-side (ground reference) to reduce component count and complexity.

One thing to note is that now that we have added MOSFETs to the rectifier special care must be taken to maintain Zero-Current Switching.



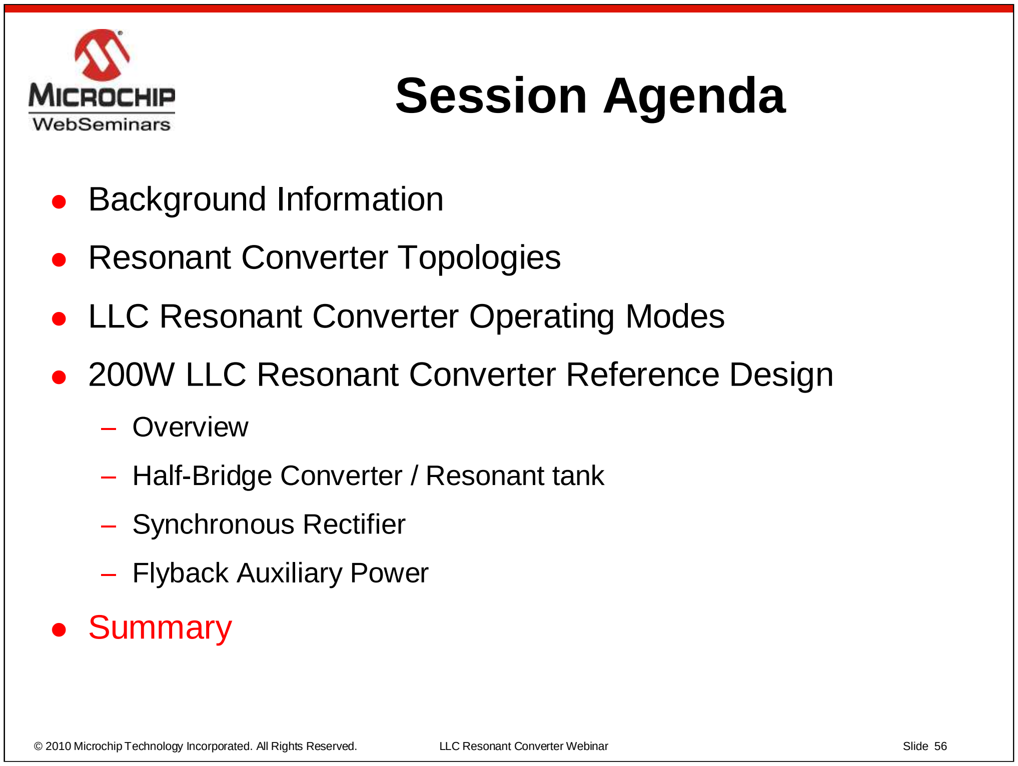
Lets now look at the auxiliary flyback circuit.



Here is a high-level block diagram of the auxiliary power section.

In this design we were targeting high efficiency and very low power at no/light load operating conditions. To do this the auxiliary circuit has been designed with an auto shut-off feature providing low stand-by power. The circuit also provides the ability to restart the auxiliary circuit in the event of a fault condition.

Upon system start-up, the flyback converter provides power to the dsPIC. When the dsPIC is up and running the output from the LLC converter (12V) will provide the necessary power for the dsPIC, essentially powering itself.



Next, let us recap what we discussed on resonant converters.

MICROCHIP WebSeminars

Summary

- Resonant Converter Background Information
- Different Resonant Converter Topologies
- LLC Resonant Converter Operation Modes
- Microchip’s 200W LLC Resonant Converter

 LLC Resonant Converter Webinar Slide 57

In this webinar, we discussed the different resonant converter topologies, operational waveforms of a LLC resonant converter, and Microchip’s 200W LLC Resonant Converter Reference Design.

From our discussions we saw that the LLC resonant converter is a suitable DC-DC converter for high-power applications with it’s high efficiency, high power density, and its ability to operate over a wide input voltage range.

Thank You

- Visit www.microchip.com/smps for more design resources
- Available for Free Download:
  - Application Note
  - Complete Source code
  - PCB Design files
  - MATLAB Simulation files

Thank you for joining me in this webinar on the LLC Resonant Converter Reference Design using the dsPIC Digital Signal Controller.

Please visit the link on this page for more design details on the LLC Resonant Converter as well as other Switch-Mode Power Supply Reference Designs.