AND9408/D

Basic Principles of LLC Resonant Half Bridge Converter and DC/Dynamic Circuit Simulation Examples

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APPLICATION NOTE

Introduction

LLC resonant half bridge converters are widely used in consumer electronics, like powering the display panel of LCD TV. However, the operating principles of a LLC resonant half bridge converter are far from apparent and intuitive [1]. This application note focuses on the intuitive and conceptual understanding of a LLC resonant converter. Some basic mathematical equations are also shown in this application note for fundamental quantitative understanding of LLC resonant half bridge converters.

Several key topics, including evolution of LLC resonant half bridge converter, basic analyzing method, DC characteristics, features of typical switching waveforms, soft−switching feature, and CCM/DCM features are covered in this application note.

For hands−on understanding of the LLC resonant half bridge converter evaluation board provided by ON Semiconductor, spice simulation circuits are provided for transient simulation and DC simulation.

Evolution of LLC Resonant Half bridge Converter

Figure 1 is a typical LLC resonant converter. Values of major circuit components are also shown in it.

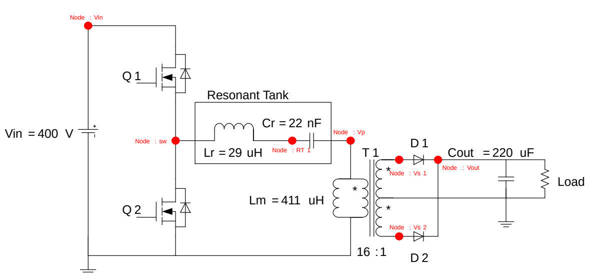

Figure 1. Transient Simulation Circuit of LLC Resonant Half Bridge Converter

While the LLC resonant half bridge converter is complicated, its intrinsic structure is very simple. It starts from a voltage divider and then adds isolation and rectification to output. With the half bridge input, the LLC resonant half bridge converter topology is formed.

The evolution has the following procedures as shown in the next three sections.

Regular Voltage Divider and Voltage Divider with Resonant Tank

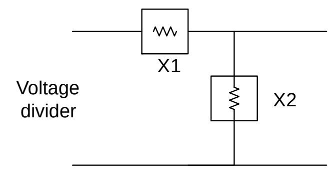

Figure 2. A Voltage Divider

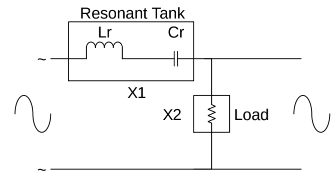

Figure 3. An AC Voltage Divider Formed by a Resonant Tank

As shown in Figure 2, a regular voltage divider converts a higher voltage to a lower voltage. The same effect can be achieved by a resonant tank and a load resistance [2], as shown in Figure 3. In Figure 3, the steady state output voltage is about the same as the input voltage when the circuit operates at its resonant frequency. The output voltage is less than input voltage when circuit is not operating at its resonant frequency. The voltage divider ratio is frequency dependent.

Square Wave Input and Transformer Isolated Output

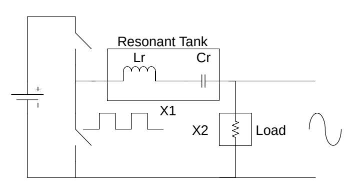

Figure 4. A DC/AC Resonant Converter

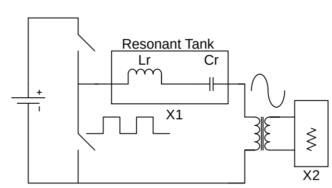

Figure 5. A DC/AC Resonant Converter with Transformer Isolated Load

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Now as shown in Figure 4, the input of a voltage divider is formed by square wave, rather than a single frequency sinusoidal input. At steady state, the high frequency harmonic waveforms of square wave input are filtered by the resonant tank, which results in sinusoidal load current. The sinusoidal output current is then isolated from resonant tank by a transformer, which results in circuit shown in Figure 5.

Output Rectification and Soft Switching at Input

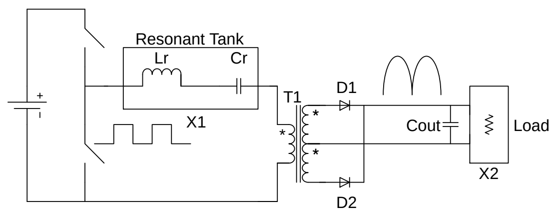


Figure 6. A DC/DC Resonant Converter

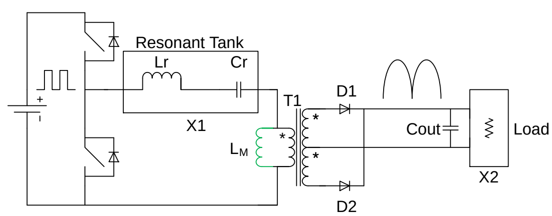


Figure 7. A DC/DC Resonant Converter with Soft ZVS Switching

To obtain DC voltage, output current of Figure 5 is rectified and stabilized by a large capacitance, providing a stable DC voltage and power on the load, as shown in Figure 6. When the circuit in Figure 6 operates at resonant frequency, the input current and output current are exactly in phase, which means that both high side and low side switches are switching with zero current. However, this benefit does not exist when the switching frequency is deviates from resonant frequency. To achieve soft switching in the vicinity of the resonant frequency, a magnetizing current is developed within the transformer. This magnetizing current the phase node to ground before the low side turns on and raises the phase node to the input voltage before the high side turns on, creating ZVS while switching on. By controlling the magnetizing current of transformer, the switching off loss of high side and low side can be minimized.

As a voltage divider, the output voltage is less than the input voltage. However, a LLC resonant converter can operates in a mode that increases rather than decreases the voltage. On the condition that Lm participates in the resonant tank as a resonant inductor, the output voltage is the voltage of resonant inductor, which could results in output voltage much higher than the input voltage.

A regular LLC resonant half bridge converter works a combination mode of a voltage divider and amplifier of resonant inductor voltage of the resonant tank.

At the resonant frequency, impedance of resonant tank is zero, which means the input voltage is 100% applied on the load. As frequency deviates from the resonant frequency, the impedance of resonant tank is larger and larger, which means the voltage on load is lower and lower. By varying the operating frequency, the output power can be controlled.

Some basic features of LLC resonant half bridge converter include HS&LS are 50% duty cycle, frequency variation controls load current, CCM/DCM is defined by rectifier current, not inductor current, and magnetizing current of transformer is the soft switching current for ZVS switching of Q1 and Q2.

Basic Analysis Method

Fundamental Harmonics Approximation [3]

In application, LLC resonant converter works around the frequency of resonant tank (formed by Lr, Cr). Due to the nature of LC filter, only the fundamental frequency of the input voltage can pass through the filter. All the harmonics are filtered by the resonant tank. Based on this fact, the topology of LLC resonant converter could be simplified to the circuit shown in Figure 8. In Figure 8, “Rac” is the reflected load from secondary side of transformer to primary side of transformer when only the fundamental harmonics is considered.

$$Rac = \frac{8}{\pi^2} \times N^2 \times R_{LOAD} \qquad \text{(eq. 1)}$$

Here, N is the transformer turn ratio of primary side and secondary side.

Two Operating Modes [4]

Depending on whether transformer is driving power to the output or not, the circuit of Figure 8 has two operating modes. One mode is Rac=0, which means the magnetizing inductance is cut off from circuit. This interval happens when the transformer is driving power to the output, resulting in the primary side of the transformer been clamped to a constant voltage (the output voltage reflected to primary side of transformer). The other mode is that Rac=8, which means Rac is cut off from circuit. This mode happens when transformer stops driving power to output. Both modes are shown in Figure 9 and Figure 10 respectively.

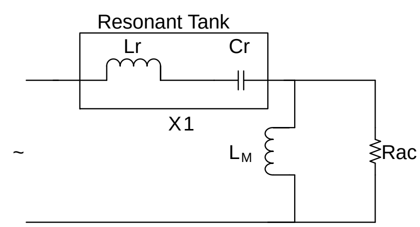


Figure 8. Simplified LLC Resonant Converter under Fundamental Harmonics Appropriation

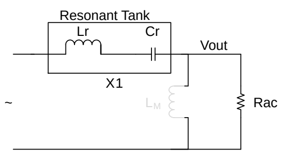


Figure 9. Operating Mode #1: Rac = 0

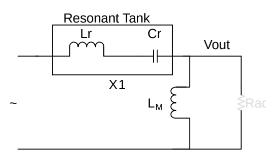


Figure 10. Operating Mode #2: Rac = ∞

It is interesting to see that, for the operating mode #1, the maximum output voltage is equal to input voltage, which happens when impedance of resonant tank is zero. For the operating mode #2, the output voltage is the voltage on magnetizing inductor, which is the resonant voltage of the magnetizing inductance and could be way higher than input voltage. This is the basic DC characteristics of LLC resonant converter.

In regular operating mode of LLC resonant converter, 0<=Rload<∞, both operating modes happen in one switching cycle.

Two Resonant Frequency of LLC Resonant Converters [5]

There are two resonant frequencies in a LLC resonant half bridge converter. One is resonant frequency at operating mode #1, shown in Figure 9 operating mode #1: Rac=0. The resonant frequency of mode #1 is expressed by Equation 2. In the vicinity of fr1, output voltage is equal or less than input voltage.

$$f_{r1} = \frac{1}{2\pi\sqrt{Lr \times Cr}} \qquad \text{(eq. 2)}$$

The other frequency is the resonant frequency at operating mode #2, shown in Figure 10. The resonant frequency of mode #2 is expressed by Equation 3. In the vicinity of fr2, the output voltage is higher than input voltage.

$$f_{r2} = \frac{1}{2\pi\sqrt{(Lr + Lm) \times Cr}} \qquad \text{(eq. 3)}$$

Two Key Parameters: m and Q

The operating region of LLC resonant half bridge converters is in the vicinity of fr1. In order to quantitatively understand the impact of gain at frequency fr2 on gain at fr1, a parameter, m, is introduced to describe the distance between two frequencies fr1 and fr2. Equation 4 is the definition of "m".

$$m = \frac{Lm}{Lr} \qquad \text{(eq. 4)}$$

When m=0, it means Lm=0 and the distance from fr1 and fr2 is zero. However, at this condition the voltage gain at frequency fr2 is also zero. Therefore, the impact of the gain at fr2 on the gain at fr1 is zero. At this condition, the maximum gain is always 1 and happens at resonant frequency fr1.

When m=0, it means Lm=0, the distance from fr1 to fr2 is fr1. Gain at fr2 has a certain impact on gain at fr1. Assuming the frequency fr1 is high enough to be out of the selection band of the resonant tank (formed by Lr+Lm and Cr) at resonant frequency fr2, the impact of the gain at fr2 on the gain at fr1 is nearly zero as well. This assumption is generally true because fr1 is usually around 200 kHz, which is more than 5 decades away from 1 Hz.

For the two most extreme cases shown above, the impact of the gain at fr2 on the gain at fr1 is both zero. The most impact of the gain at fr2 on the gain at fr1 comes when 0<m<∞. This feature is shown in Figure 11. This impact is elaborated in the next section.

In a LC resonant circuit, quality factor Q is the parameter to describe how fast the resonant gain drops when deviating from the resonant frequency. The definition of Q is shown by Equation 5.

$$Q = \frac{\sqrt{\frac{Lr}{Cr}}}{Rac} \qquad \text{(eq. 5)}$$

Here, Rac is the load resistance reflected to primary side of transformer under the fundamental harmonic approximation, shown in Equation 1.

At a specific fr1, higher Q means faster voltage gain drop when deviating from fr1. The higher the Q, the less the gain at fr2 impacts the gain at fr1. Q directly impacts the voltage gain between fr1 and fr2.

In a LLC circuit design, Q needs to be controlled within a certain range, so that the voltage stress on the resonant inductance or resonant capacitor is under minimized.

DC Characteristics and Operation Point Placement

To understand the operation of LLC resonant circuits, it is necessary to understand DC characteristics at various frequencies, especially in the vicinity of fr1 and fr2.

A frequency sweep for the circuit shown in Figure 8 yields the DC characteristics of the resonant converter, as shown in Figure 12. By varying the value of the load resistance, a family of DC gain curves over a frequency range is created.

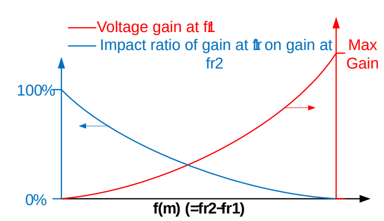


Figure 11. Gain at fr1 and Impact Ratio of Gain at fr1 on Gain at fr2 as a Function of the Distance between fr1 and fr2

The most apparent feature of the DC characteristics shown in Figure 12 is the two resonant frequencies, fr2 and fr1. These two resonant frequencies divide the frequency range into three regions. Given that a resonant tank exhibits capacitive characteristics when below its resonant frequency and inductive characteristics when above, three regions can be identified in Figure 13: capacitive for fr1 and capacitive for fr1 and inductive for fr2, and inductive for both fr1 and fr2.

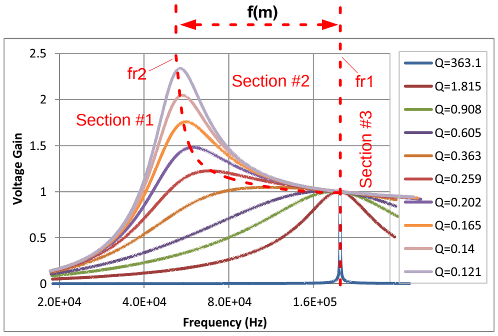


Figure 12. DC Characteristics of LLC Resonant Half Bridge Converter

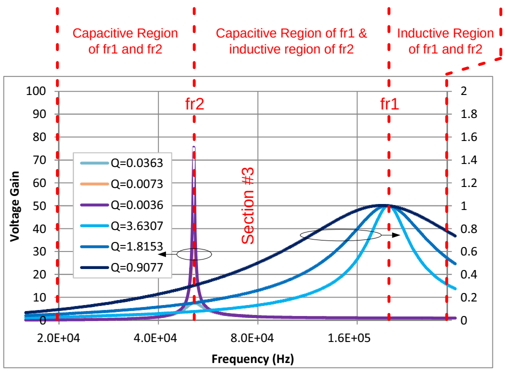


Figure 13. Three Regions of DC Characteristics of LLC Resonant Half Bridge Converter

In the region between fr1 and fr2, there is a competition between capacitive characteristics of fr1 and inductive characteristics of fr2. This competition results in the top half of the region is inductive, in which gain decreases as frequency increases, the bottom half is capacitive, in which gain increases as frequency increases. This result is shown in Figure 12, where section #1 is marked as capacitive region, section #2 is marked as inductive region, and section #3 is marked as inductive region.

The regular operating point of LLC resonant converter resides in section #2 near fr1 due to lower switching frequency and stable voltage gain. Here, one can see that all the curves go through the point of (fr1, 1), which means that the operating frequency won't change too much while load varies. This feature limits operating frequency into a relative narrow range and gives better stability.

Various Operating Mode of LLC Resonant Half Bridge Converter

There are many operating modes of LLC resonant converters. The most frequently used operating mode is in the vicinity of fr1. It is of greater interest to analyze the operation exactly at frequency fr1 and slightly higher and lower than fr1.

Operation Mode #1: fs=fr1

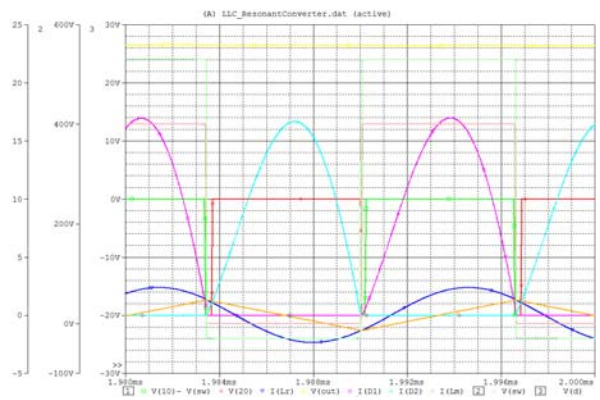
This mode is the basis of all other modes. At this mode, ringing current of resonant tank is exactly in phase with load current.

Resonant Cycle and Operation Intervals

1. high side turn−off to low side turn−on

When the high side is turning off, the primary current of the transformer (blue line) resonates back to magnetizing current (coral), as shown in Figure 14. The resonant current flows positively from phase node to ground. After the high side is fully turned off, the resonant current freewheels through diode of low side MOSET, which clamps drain−source voltage of low side MOSFET to zero.

As the resonance current drops below the magnetizing current, the primary current of the transformer become negative, driving current through D2 to load (assuming magnetizing current is sufficiently small). From this moment, the secondary side of transformer starts rectifying the negative waveforms. D2 starts to conduct load current, while D1 is off.



Blue: resonant current, red: driving pulse of high side MOSFET,
Green: driving pulse of low side MOSFET,
Magenta: current of D1,
Cyan: current of D2

Figure 14. Waveforms of LLC Resonant Half Bridge Converter

2. low side turn−on to low side turn−off

After the drain−source voltage of the low side MOSFET is clamped to zero volts, the low side MOSFET is turned−on. This switching−on transient is Zero Voltage switching. During this interval, the resonant current starts decreasing from magnetizing current reaching negative current. Transformer current on primary side reverses direction and stays negative for 180 degrees.

3. low side turn−on to high side turn−on

At the moment of low side turn−off, the resonant current is negative and equal to magnetizing current in magnitude. The negative current flows through body diode of the high side MOSSFET clamping high side MOSFET's drain−source voltage to zero volts. After that, the high side MOFET is turned−on under ZVS conditions.

Operation Mode #2: fs>fr1

When Compared to fs=fr1, the waveforms of fs>fr1 are a little different. The major difference is that at heavy load, the resonant current is of higher magnitude than the magnetizing current when the high side or low side is turning−off. With this condition, when phase node switches high or low, the applied phase node voltage will force resonant current to go down to the level of magnetizing current. At the same time, the voltage on primary side of transformer remains N*Vout. The key feature at this moment is that the resonant current drops in a straight line with constant slope (This slope is equal to (Vin–N*Vout)/Lr), as seen in Figures 15 and 16.

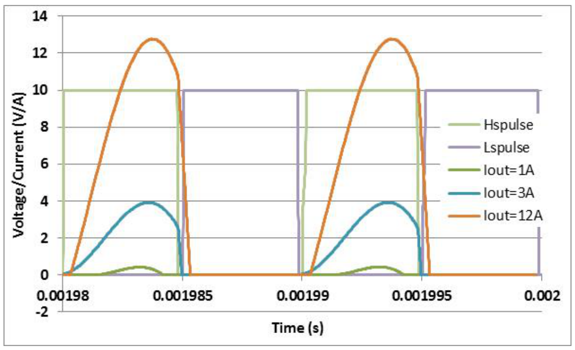


Figure 15. Rectifier Current of D1 at fs>fr1

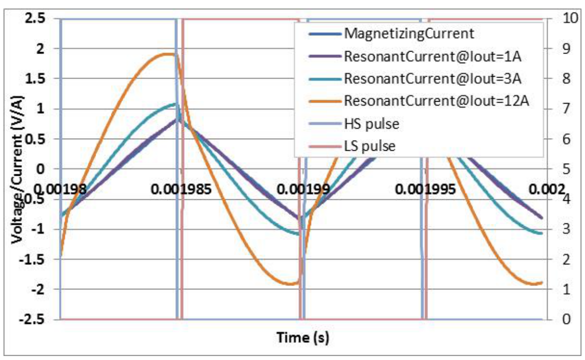


Figure 16. Resonant Current and Magnetizing Current on Primary Side

Figure 17 shows the sequence of phase node voltage (blue line on top) and voltage on the primary side of MOSFETs (oral, green, purple lines). There is a delay in phase between phase node voltage and voltage on the primary side of MOSFET. This delay is the interval driving resonant current back to magnetizing current. At the end of this delay, current of D1 and D2 alternates. As can be seen in Figure 17, the delay is related to the load current. The higher the load current is, the longer the delay is. This is because it takes more time to drive the resonant current to magnetic current at higher loads.

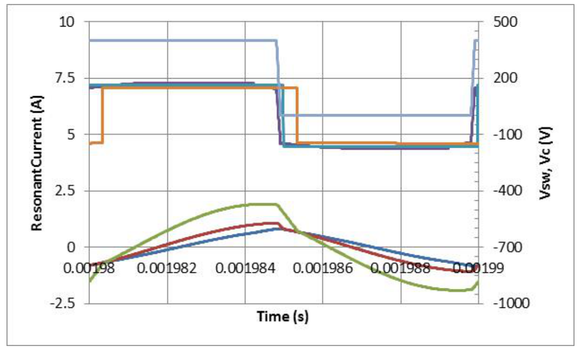


Figure 17. Phase Node Voltage and Primary Side Voltage of Transformer

Operation Mode #3: fs<fr1

Unlike the situation fs>fr1, in which resonant current has not fallen down to the magnetizing current when the MOSFET are switching, the resonant current has already fallen down to the magnetizing current before the MOSFET is switching, as is shown in Figure 18. After that, if the resonant current is high enough, two rectifier diodes conduct current alternatively, which is the CCM. If resonant current is not high enough to turn−on the rectifier, the rectifier will go into DCM mode. This is the key characteristic of switching below fr1. CCM/DCM is elaborated in a later section.

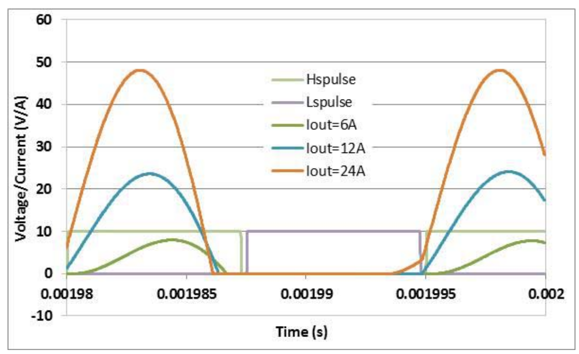


Figure 18. Current of D1 at fs<fr1

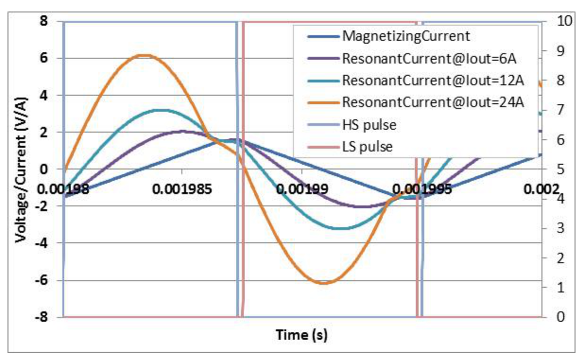


Figure 19. Resonant Current and Magnetizing Current

Figure 19 shows resonant current and magnetizing current on the primary side of the transformer. As can be seen, the resonant current resonates back to magnetizing current before the high side is turned−off, leaving an interval for DCM mode or CCM mode, depending on the resonant current level. This interval is more clearly seen in Figure 20. The voltage of primary side (oral, light blue and purple lines) drops to zero or an intermediate voltage after the resonant current drops to the magnetizing current. After that, if resonant current is high, the magnetizing inductor on primary side of transformer is either functioning sinusoidal with resonant tank or clamped by the output voltage if resonant current is high enough to drive current to the load.

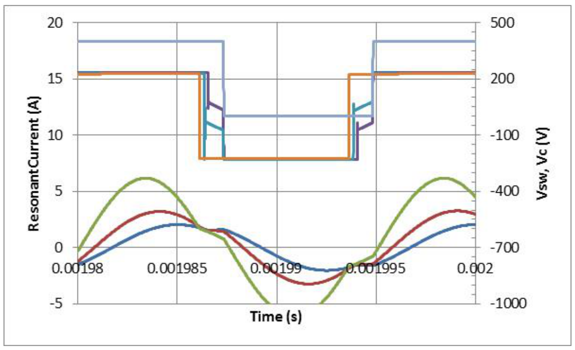


Figure 20. Phase Node Voltage and Primary Side Voltage of Transformer

Zero Voltage−Switching and Zero Current Switching Features

The soft switching turn−on is achieved by the magnetizing current of transformer, which makes the circuit working in inductive condition, as shown in Figure 21. For the capacitor, ZCS turn−off could be achieved, as shown in Figure 22.

The transformer is designed to have sufficient magnetizing inductance to maintain the magnetizing current. The smaller magnetizing inductance is, the higher magnetizing current is. This behavior of magnetizing inductance is exactly the same with regular inductance. Without magnetizing current, the switching of the high side and low side MOSFETs is zero current switch−on at fr1. If the switching frequency is not exactly at resonant frequency fr1, soft switching−on cannot be achieved for the low or zero magnetizing current cases, as shown in Figure 23 and Figure 24.

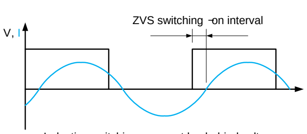


Figure 21. Phase Relation of Voltage and Current of an Inductor

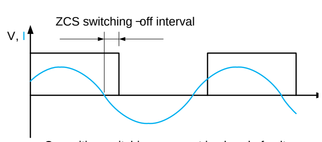


Figure 22. Phase Relation of Voltage and Current of a Capacitor

For the rectifier on the second side of the transformer it is always zero current switching, which means Qrr loss is zero.

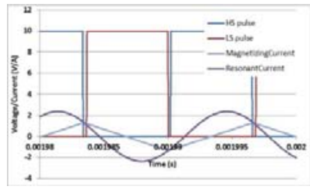


Figure 23. Switching with Sufficiency Magnetizing Current

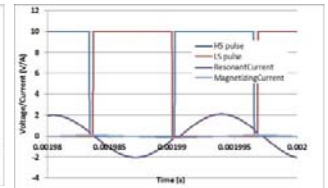


Figure 24. Switching without Sufficiency Magnetizing Current

Continuous Current Mode (CCM) and Discontinuous Current Mode (DCM)

The CCM and DCM mode of LLC resonant converter is not determined by inductor current, but by rectifier current. If the rectifier is not continuously conducting current to output, it is DCM. Otherwise, it is CCM.

The rectifier current (diode current of rectifier) is expressed by Equation 6. As can be seen in Equation 6, I_D is positive and therefore CCM when Ir>Im. Otherwise, DCM occurs. In another word, if the resonant current is sufficiently high to provide current higher than magnetic current when primary side voltage of transformer is clamped reversely by n*Vout, it is CCM. If the resonant current is not high enough to be higher than magnetic current when voltage is clamped reversely, it is DCM. If magnetizing current is zero, there is no DCM.

$$I_D = (I_r - I_m) \times N \qquad \text{(eq. 6)}$$

Here, Ir is the resonant current of Lr, Im is the magnetizing current of the transformer.

There are many factors associated with the DCM [2], like switching frequency, characteristics of resonant tank, input to output ratio and load current. As a LLC resonant converter, the major factor that relates with operating in DCM or CCM is load current. At high load current, it tends to work in CCM; at light load situation, it tends to work in DCM.

In order to show the impact of load current on DCM and CCM, three load conditions are simulated, as shown in Figure 25. At high load currents, D1 and D2 alternately conduct load current. This is CCM. At light load, there are some intervals that the rectifiers do not provide any current to the load, which is the DCM.

The simplified circuits of LLC resonant converters at CCM/DCM are shown in Figures 9 and 10 respectively. For LLC resonant converters working in DCM, the circuit switches between circuits of Figures 9 and 10 in one switching cycle.

Quantitatively, the boundary of DCM and CCM is a function of four parameters: Vout, Vs/Vp, Iload, and Lm.

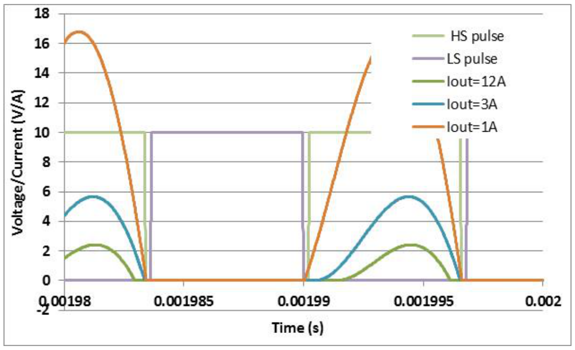


Figure 25. Current of D1 at Various Load Conditions

DC/Transient Simulation Circuits of LLC Resonant Half Bridge Converter

Basic simulation information is shown below. These simulation parameters are designed based on the evaluation board NCP1397GANGEVB [6]. Here is the simulation circuit.

1. Vin = 400 V, Vout = 12 V, Iout = 0−20 A
2. Simulation circuit: Q1&Q2 are V−swtich: Ron = 200 mΩ, Coss = 200 pF.
3. Resonant tank is: Lr = 29 μH, Cr = 22 nF, (fr1 = ~200 kHz)
4. Transformer is: 16:1, Lm = 411 μH.
5. Output capacitance: Cout = 200 μF

Transient Simulation Circuit

The critical node names of transient simulation circuit are shown in Figure 1. This node names are used in simulation code.

Transient Simulation Code

```
**Simulation circuit of half bridge LLC resonant converter
**ON semiconductor

*converter parameters
.param Ts=6.667u;6.667us; 150kHz,
.param Vin=400 Iout=20 Lm=411u

*driver parameters
.param delay_hs={20n} tr_hs=20n tf_hs=20n
duty_cycle={(Ts-deadtime*2-(tr_hs+tf_hs+tr_ls+tf_ls))/2}
.param deadtime=200ns
.param delay_ls={duty_cycle+tr_hs+tf_hs+deadtime+delay_hs}
.param tr_ls=20n tf_ls=20n duty_prime={duty_cycle};

*sweeping parameters
.param RDSon={200} Cgs={760p} Cgd={5p} Cds={200p }

*Sweep parameters
.step param Iout list 5,10,15,20,

*SWITCH DRIVER
VCTRL1 10 sw PULSE(0V 12V {delay_hs} {tr_hs} {tf_hs} {duty_cycle} {Ts})
Rgh 10 hg 5

VCTRL2 20 gnd PULSE(0V 12V {delay_ls} {tr_ls} {tf_ls} {duty_prime} {Ts})
Rgl 20 lg 5;

* INPUT VOLTAGE
Vin Vin gnd DC {Vin}

*high side MOSFET
Rdh Vin hd 0.1m; used for channel current sensing
Shs hd hs hg hs Smod
.MODEL Smod VSWITCH(Ron={RDSon} Roff=100MEG Von=12V Voff=0V)
Cgshs hg hs {Cgs}
Cgdhs hg Vin {Cgd}
Cdshs Vin hs {Cds}
Dfwhs hs hd Dmod
.MODEL Dmod D (IS=1e-12, CJO=1P)
Lsh hs sw 15n

*low side MOSFET
Rdl sw ld 0.1m ; used for channel current sensing
Sls ld ls lg ls Smod
Cgsls lg ls {Cgs}
Cgdls lg sw {Cgd}
Cdsls sw ls {Cds}
```

```
Dfwls ls ld Dmod
Lsl ls gnd 15n

*here is resonant tank
Rlr sw int1 1m
Lr int1 RT 29u ic=0
Cr RT Vp 22n ic={Vin/2}

*transformer
Lp Vp int2 {Lm} ic=0
Rlp int2 gnd 1m
Ls1 Vs1 0 {Lm/256} ic=0 ; voltage ratio=sqrt(256)=16;
Ls2 0 Vs2 {Lm/256} ic=0
K1 Lp Ls1 Ls2 1

*here is the sensed magnetizing current of transformer
Elm 100 0 value={V(Vp)-V(int2)}
Lm 100 101 {Lm} ic=0
Rlm 101 0 1m

*here is output rectifier
D1 Vs1 Vout Dmod
Rd1 Vs1 0 1meg
D2 Vs2 Vout Dmod
Rd2 Vs2 0 1meg
Cout Vout 0 200u ic=12
*load
Rload Vout 0 {12/Iout}

*connect grounds at one point
Rgnd gnd 0 1u

* ANALYSIS
.TRAN     1n 1000u 993u 10n; 1.5 periods simulation
.PROBE ;-s(W(Rload))/s(W(Vin)+W(VCTRL1)+W(VCTRL2))
.END
```

DC Characteristics Simulation Circuit

The simulation circuit is shown in Figure 8.

```
**Simulation circuit of half bridge LLC resonant converter
**ON semiconductor

*converter parameters
.param variable=1
.param Lm=411u

*Sweep parameters
.step param variable list 10, 20, 40;

Vs sw 0 AC 1 0

*here is resonant tank
Rlr sw int1 1m
Lr int1 RT 29u
Cr RT Vp 22n

*transformer
Rac Vp 0 {variable}
Lp Vp int2 {Lm} ic=0
Rlp int2 0 1m

* ANALYSIS
.AC DEC 2000 1kHz 500kHz;
.PROBE
.END
```

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