Half Bridge LLC Tank Circuit Sample Design

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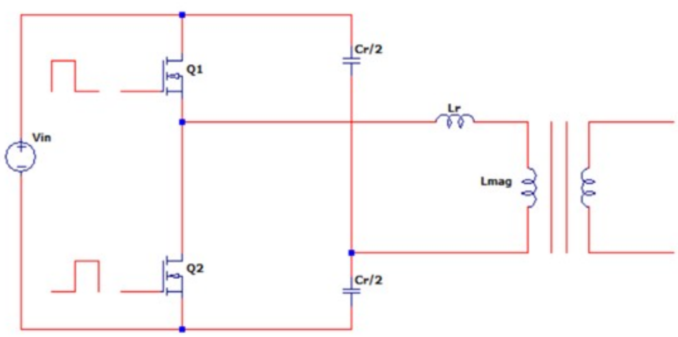
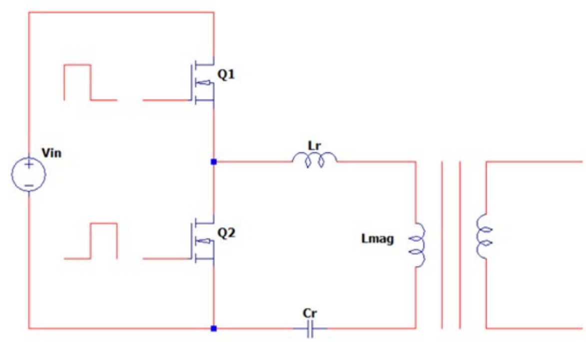
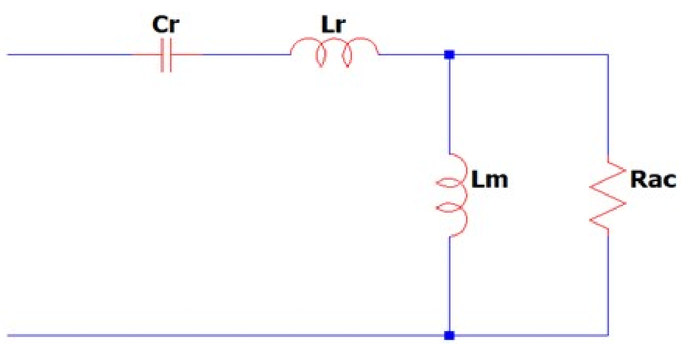






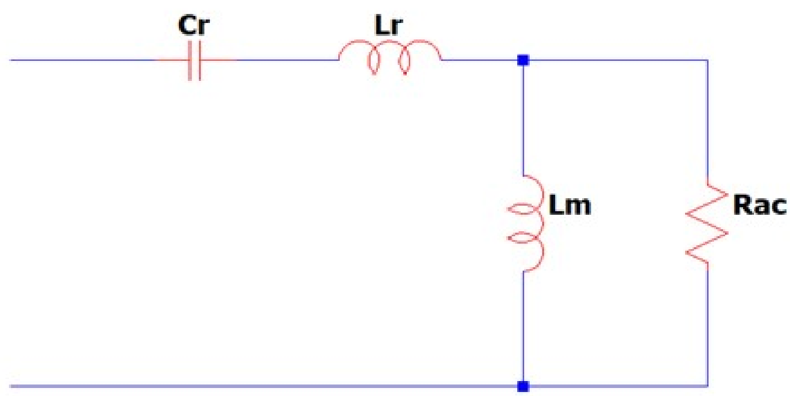
Note: This sample design is intended to help engineers to establish a starting point in designing half bridge LLC resonant converter. It is the responsibility of the engineer to fine tune and optimize the values derived here.

(1) Analysis and Calculations

1.1 Equivalent Circuit

This is an AC circuit model for Half Bridge LLC resonant converter. It is derived using first harmonic approximation (FHA).

A very detailed derivation is found in electronicsbeliever.com in the link below
https://electronicsbeliever.com/how-to-derive-llc-converter-ac-circuit/



1.2 Input Voltage

These are given values during the design stage. In this design sample, the input voltage is wide range. This is normal for a rectified voltage which is filtered by bulk capacitance.

$Vin\_nom := 390\ V$ This is the nominal input voltage to the LLC
$Vin\_min := 330\ V$ This is the minimum input voltage to the LLC
$Vin\_max := 420\ V$ This is the maximum input voltage to the LLC

1.3 Output Voltage

These are given values during the design stage. In this sample design, the output voltage of the LLC is not variable. The only factor is ripple voltage but it is negligible in this section.

$Vout\_nom := 15\ V$
$Vout\_min := 15\ V$
$Vout\_max := 15\ V$

1.4 Load Currents

These are given values during the design stage. In this sample design, the load current is fixed in all voltage output.

$Iout\_NomVout := 24\ \mathbf{A}$
$Iout\_MinVout := 24\ \mathbf{A}$
$Iout\_MaxVout := 24\ \mathbf{A}$

1.5 Frequency

$Fresonance := 120\ \mathbf{kHz}$ Desired resonant frequency
$Foperation\_max := 400\ \mathbf{kHz}$ Maximum switching frequency allowable

If the LLC has fixed operating point such as fixed input and output voltages, the resonant frequency will be observed all the times. But since the input voltage in this sample design is wide, thus the operating frequency will go out of resonance.

1.6 Dead Time and Delay

$Tdeadtime\_total := 330\ \mathbf{ns}$

Total dead time is the sum of the FW dead time and all the delays introduced in the hardware. If you cannot quantify the hardware portion, it is okay to use the FW dead time. Fine tuning can be done in actual.

1.7 Output Power

$Pout\_NomVout := Iout\_NomVout \cdot Vout\_nom$
$Pout\_NomVout = 360\ \mathbf{W}$

$Pout\_MinVout := Iout\_MinVout \cdot Vout\_min$
$Pout\_MinVout = 360\ \mathbf{W}$

$Pout\_MaxVout := Iout\_MaxVout \cdot Vout\_max$
$Pout\_MaxVout = 360\ \mathbf{W}$

1.8 MOSFET Parameters

$Cstray := 10\ \mathbf{pF}$ Layout capacitance and transformer winding capacitance
$COSS := 100\ \mathbf{pF}$ MOSFET output capacitance

$C\_ZVS := 2 \cdot COSS + Cstray$
$C\_ZVS = \left(2.1 \cdot 10^{-10}\right)\ \mathbf{F}$ Capacitance at ZVS mode

1.9 Design the Transformer Turns Ratio, n

$$n\_calculated := \frac{1}{2} \cdot \frac{Vin\_nom}{Vout\_nom}$$

$$n\_calculated = 13$$

$$n\_selected := 13$$

n_selected is the turns ratio to use. In case the result of the calculation is not a whole number, input here the nearest whole number.

1.10 Gain Calculation

$$Gain\_max := 2 \cdot n\_selected \cdot \frac{Vout\_max}{Vin\_min}$$
$$Gain\_max = 1.182$$

$$Gain\_min := 2 \cdot n\_selected \cdot \frac{Vout\_min}{Vin\_max}$$
$$Gain\_min = 0.929$$

$$Gain\_nom := 2 \cdot n\_selected \cdot \frac{Vout\_nom}{Vin\_nom}$$
$$Gain\_nom = 1$$

1.11 Normalized Frequency

$$Fnormalize\_max := \frac{Foperation\_max}{Fresonance}$$

$$Fnormalize\_max = 3.333$$

1.12 Equivalent Resistance to Primary (Rac)

$$Rac\_NomVout := \frac{8}{\pi^2} \cdot n\_selected^2 \cdot \frac{Vout\_nom^2}{Pout\_NomVout}$$

$$Rac\_NomVout = 85.616\ \Omega$$

$$Rac\_MaxVout := \frac{8}{\pi^2} \cdot n\_selected^2 \cdot \frac{Vout\_max^2}{Pout\_MaxVout}$$

$$Rac\_MaxVout = 85.616\ \Omega$$

$$Rac\_MinVout := \frac{8}{\pi^2} \cdot n\_selected^2 \cdot \frac{Vout\_min^2}{Pout\_MinVout}$$

$$Rac\_MinVout = 85.616\ \Omega$$

1.13 Inductance Ratio

$$\lambda := \frac{1 - Gain\_min}{Gain\_min} \cdot \frac{Fnormalize\_max^2}{Fnormalize\_max^2 - 1}$$

$$\lambda = 0.085$$

1.14 Quality Factor, Q

Q at full load and minimum input

$$Q\_ZVS\_Vinmin\_FullLoad := 100\% \cdot \left(\frac{\lambda}{Gain\_max} \cdot \sqrt{\frac{1}{\lambda} + \frac{Gain\_max^2}{Gain\_max^2 - 1}} \right)$$

$$Q\_ZVS\_Vinmin\_FullLoad = 0.28$$

Q at no load and maximum input

$$Q\_ZVS\_Vinmax\_NoLoad := \frac{2}{\pi} \cdot \frac{\lambda \cdot Fnormalize\_max}{(\lambda + 1) \cdot Fnormalize\_max^2 - \lambda} \cdot \frac{Tdeadtime\_total}{Rac\_NomVout \cdot C\_ZVS}$$

$$Q\_ZVS\_Vinmax\_NoLoad = 0.275$$

1.15 Choosing the Right Q for ZVS

The smaller value should be used

```
Q_ZVS := || if Q_ZVS_Vinmin_FullLoad < Q_ZVS_Vinmax_NoLoad
         ||   || Q_ZVS_Vinmin_FullLoad
         || else
         ||   || Q_ZVS_Vinmax_NoLoad
```

$$Q\_ZVS = 0.275$$

1.16 Minimum Operating Frequency

Minimum operating frequency is happening at full load, max output voltage and minimum input voltage. For non trimmable output, only full load and minimum input voltage are the factors.

$$Q_{max} := \begin{cases} \left(\dfrac{\lambda}{Gain\_max} \cdot \sqrt{\dfrac{1}{\lambda} + \dfrac{Gain\_max^2}{Gain\_max^2 - 1}}\right) & \text{if } \left(\dfrac{\lambda}{Gain\_max} \cdot \sqrt{\dfrac{1}{\lambda} + \dfrac{Gain\_max^2}{Gain\_max^2 - 1}}\right) > Q\_ZVS \\ Q\_ZVS & \text{else} \end{cases}$$

$$Q_{max} = 0.28$$

$$Foperation\_min := Fresonance \cdot \sqrt{\dfrac{1}{1 + \dfrac{1}{\lambda} \cdot \left(1 - \dfrac{1}{Gain\_max^{\left(1 + \left(\frac{Q\_ZVS}{Q_{max}}\right)^4\right)}}\right)}}$$

$$Foperation\_min = \left(5.814 \cdot 10^4\right) \frac{1}{s}$$

1.17 Resonant Network Values

$$Cr := \frac{1}{2 \cdot \pi \cdot Fresonance \cdot Q\_ZVS \cdot Rac\_NomVout}$$

$$Cr = \left(5.63 \cdot 10^{-8}\right) \, F$$

$$Lr := \frac{Q\_ZVS \cdot Rac\_NomVout}{2 \cdot \pi \cdot Fresonance}$$

$$Lr = \left(3.124 \cdot 10^{-5}\right) \, H$$

$$Lm := \frac{Lr}{\lambda}$$

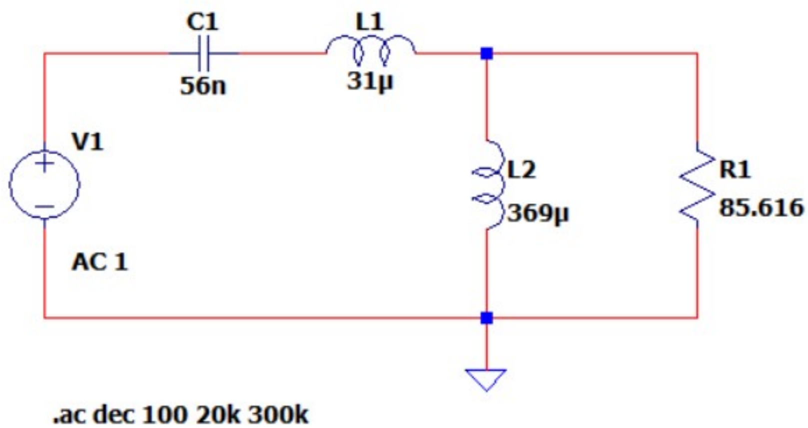
$$Lm = \left(3.696 \cdot 10^{-4}\right) \, H$$

(2) Simulations

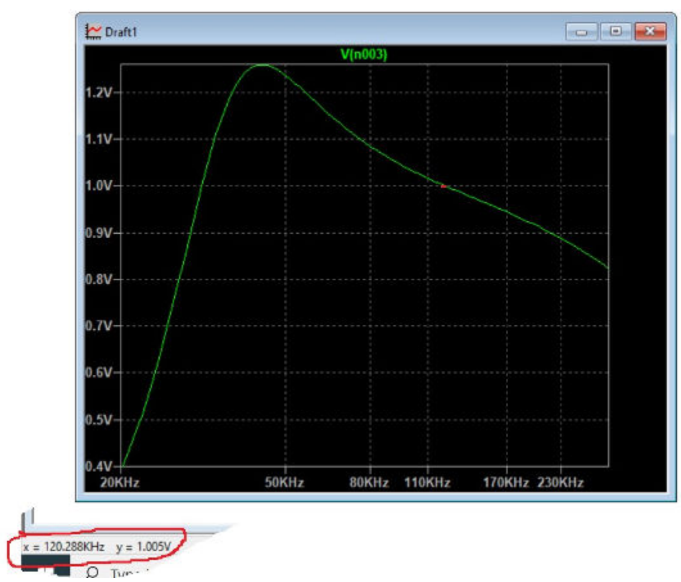
It is a great idea to use both calculations and simulations to verify each other. In this way, your confidence level is high that what you are doing is correct.

2.1 At Resonance Point (unity gain)

Below is the equivalent LLC AC circuit using the derived network values. The simulation run is AC decade with a minimum frequency of 20 kHz and a maximum frequency of 300 kHz. The complete tutorial on how to derive LLC AC circuit and how to simulate using it is can be found in electronicsbeliever.com.



Below is the frequency-gain curve of the above circuit. The x-axis is the frequency sweep from 20 kHz to 300 kHz. The y-axis is the magnitude in voltage. The simulation input is a 1V AC signal. For LLC, the output voltage across R1 in the AC circuit must be the same to the input to achieve resonance. Thus, at 1V level of the y-axis we can project the resonance frequency and it is 120 kHz.



2.2 Below Resonance (gain is higher than unity)

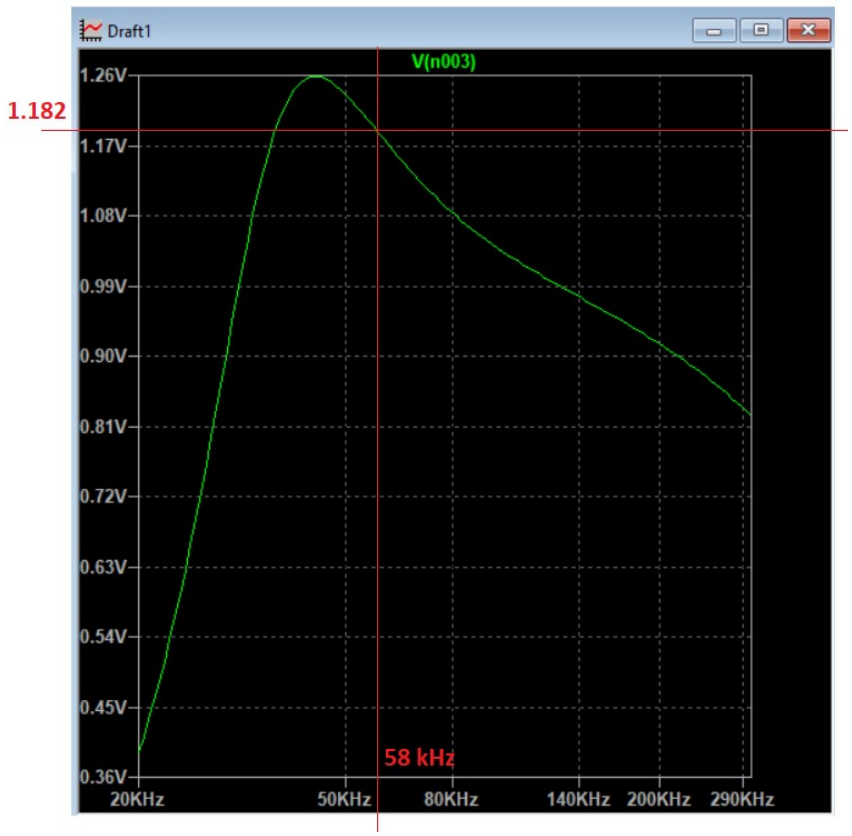
The LLC converter will go outside resonance because its input is not a fixed voltage. A gain more than unity will occur when the input voltage is at the lowest point and the output voltage is at the maximum point. This is because the tank circuit or the LLC network is designed at the nominal parameters.

In the above sample design, only the input voltage varies. Thus, it is the main contributor of the gain going more than unity.

From the above calculations, the gain is

$$Gain\_max = 1.182$$

By plotting to the frequency-gain curve, this is equivalent to around 58 kHz.



The above result coincides to the calculated minimum operating frequency above which is around 58 kHz.

$$Foperation\_min = \left(5.814 \cdot 10^{4}\right) \frac{1}{s}$$

2.3 Above Resonance (gain is lower than unity)

This condition happens at the minimum output voltage and maximum input voltage. Since the design sample above has fixed output voltage, thus only the input voltage variation dictates the minimum gain.

From the calculation above, the minimum gain is

$$Gain\_min = 0.929$$

The corresponding operating frequency of this gain is around 190 kHz.