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**SIMULATION OF A SERIES HALF BRIDGE  
LLC RESONANT CIRCUIT**  
ECE562: Power Electronics I  
COLORADO STATE UNIVERSITY

Fall 2011

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**PURPOSE:** The purpose of this lab is to simulate the LLC resonant converter using NL5 to better familiarize the student with some of its operating characteristics.

Two variants of the LLC converter are the series resonant converter and the parallel resonant converter. The LLC converter is series resonant when  $C_r$  is in series with the magnetizing inductance  $L_p/L_m$  of the transformer (shown below) and a parallel resonant converter when  $C_r$  is in parallel with the magnetizing inductance  $L_p/L_m$  as shown below.

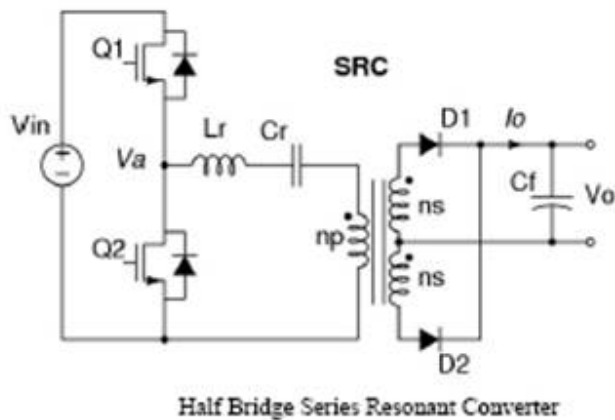
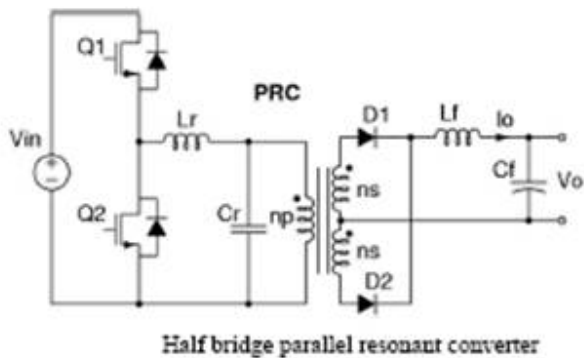
This lab will focus only on the behavior of the series resonant LLC converter operation.

The LLC converter is used with a transformer in either a full bridge or half bridge configuration. To save on parts counts, lower power LLC converters will be of the half bridge configurations as shown below (Two switches are used versus the four switches used in full bridge LLC). The LLC converter utilizes the magnetizing inductance of the transformer to construct a complex resonant tank with Buck Boost transfer characteristics in the soft-switching region. The two switches operate at a 50% duty cycle and the output voltage is regulated by varying the switching frequency of the converter. The converter has two resonant frequencies – a lower (variable- due to load  $R$ ) resonant frequency (set by  $L_m$ ,  $L_r$ ,  $C_r$  and the load resistance) and a fixed higher series resonant frequency  $F_{r1}$  (set by  $L_r$  and  $C_r$  only). The two switches can be soft switched for the entire load range by operating the converter under the inductive load region (ZVS region). It can be operated above or below the  $F_{r1}$  higher resonant frequency where  $F_{r1}$  defines the boundary between region 2 and 3 (shown later).

This lab will explore some of the following aspects of the half bridge series resonant converter:

- Three regions of operation for LLC converter
- Frequency response of LLC converter
- Input impedance of the LLC tank
- Output voltage of the LLC tank
- Inductor currents of the LLC tank
- Zero crossing of inductors currents to find resonant frequencies

- Output power of LLC tank



The graph below shows the three distinct regions that the series resonant LLC converter can be operated in. Region 1 is soft switched (ZVS) region at a frequency above the frequency of the higher resonant tank circuit. Region 2 is also a soft switched (ZVS) region with a frequency between the resonant peaks of the two tanks circuits. Operation in region 3 is below the frequency of the peak of the lower tank circuit and causes the converter to operate in the ZCS switching region (hard switching).

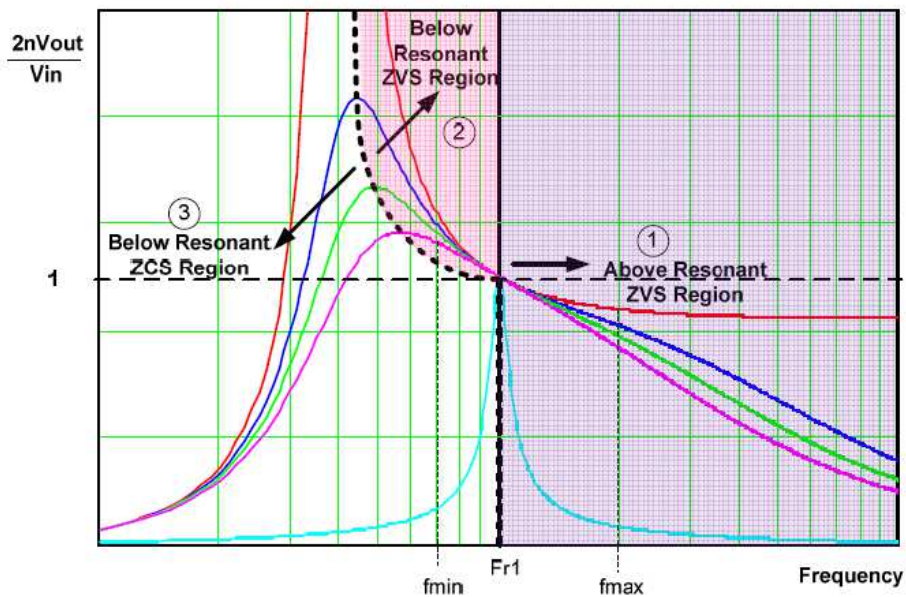


Figure 1 - Typical voltage conversion ratio of a LLC resonant converter

The following schematic shows a simplified series resonant half bridge LLC converter. The output is a tapped transformer followed by a half wave bridge rectifier. A technique called First Harmonic Approximation is sometimes used to simplify the analysis of the converter. To convert the circuit below to its FHA equivalent, all the components on the secondary side are put to the primary side. To accomplish this, all the impedances on the secondary side are multiplied by the turns ratio squared to come up with the equivalent primary side impedances. The DC switching (Square wave) voltages are converted to an AC sin wave which represents only the frequency and amplitude of the fundamental sine wave component of the Fourier transform of the switching square wave.

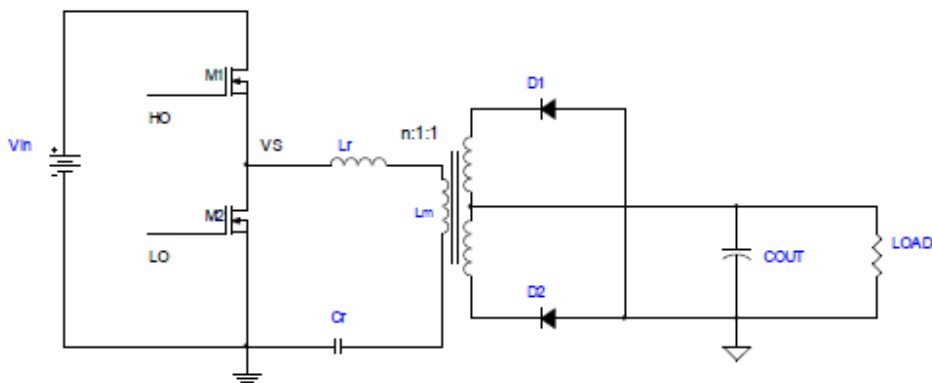


Figure 2 - Series resonant half-bridge LLC converter

The circuit below shows the simplified schematic showing a FHA equivalent of the circuit above. The load resistor impedance has been multiplied by the turns ratio of the

transformer and adjusted so that the AC power dissipation will be the same the dissipation as the circuit above. For detailed information on this conversion, please refer to International Rectifier's application note AN-1160.

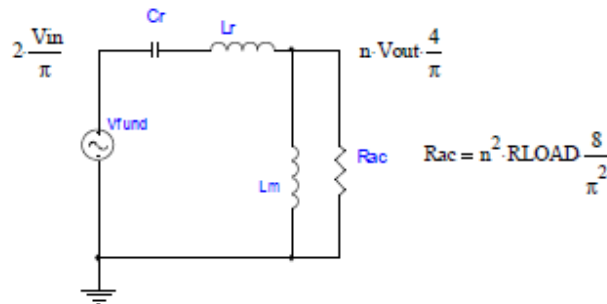


Figure 3 - The FHA (First Harmonic Balance) equivalent circuit

**NOTE:** The simulations that follow are intended to be completed with NL5. It is assumed that the student has a fundamental understanding of the operation of NL5. NL5 can be found at <http://nl5.sidelinesoft.com/>

MATLAB will be used later in the lab to solve additional parameters of the LLC converter.

Build the schematic in NL5 as shown in Figure 3 above

- **Vfund** is an AC voltage source. Set the type to 'Sin,' and the magnitude to 1 V.
- **Cr** is an ideal capacitor. Set to 22 nF.
- **Lr** is an ideal inductor. Set to 125 μH.
- **Lm** is an ideal inductor representing the magnetizing inductance of the transformer. Set it to 500 μH.
- **Rac** is an ideal resistor. Set to 157 Ω.

**HINT:** Press F3 (Schematics->components pull down) and adjust the names and values as needed. To adjust a name, select the component name and then select the upper left [a]b] symbol. To select a value, select the component on the left column of components and then type a new value in the right side component value field.

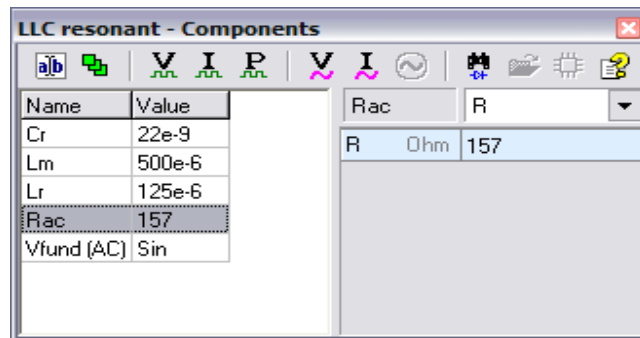


Figure 4 - Window (Press F3) to adjust name and values of components

**HINT: Rotate left or right, mirror or flip components as needed.**

To change orientation of a schematic element, use **Rotate**, **Mirror**, and **Flip** commands:

- **Rotate right (Ctrl-R).** Rotate right (clockwise).
- **Rotate left (Ctrl-L).** Rotate left (counterclockwise).
- **Mirror (Ctrl-M).** Mirror (flip around vertical axis).
- **Flip (Ctrl-F).** Flip (flip around horizontal axis).

After making name and component values adjustments, the First Harmonic Approximation of the series resonant LLC converter should look like the schematic below.

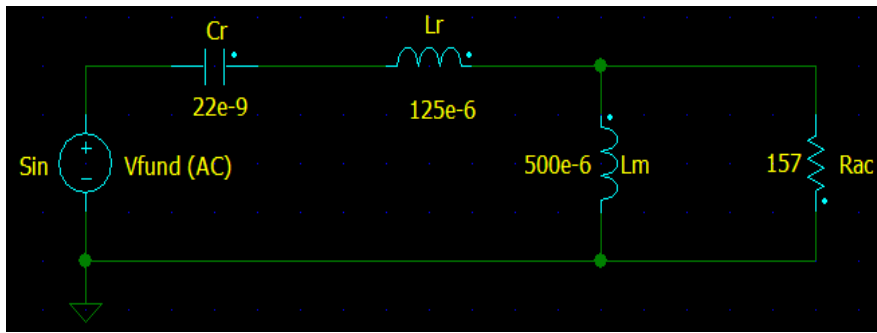


Figure 5 - FHA representation of series resonant LLC converter in NL5

Select AC->Settings and set the 'AC Settings' parameters as follows:

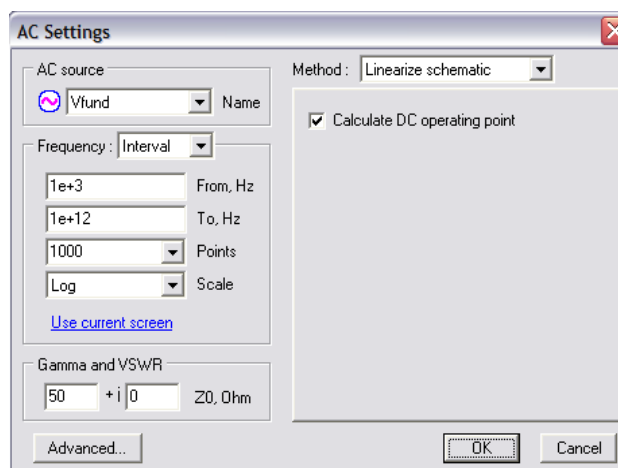
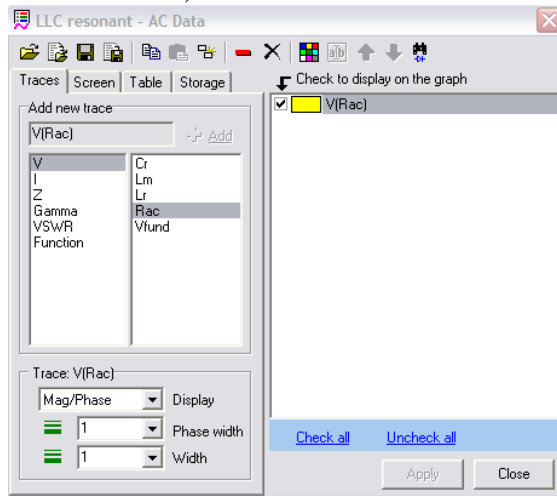


Figure 6 - AC parameter settings for FHA analysis

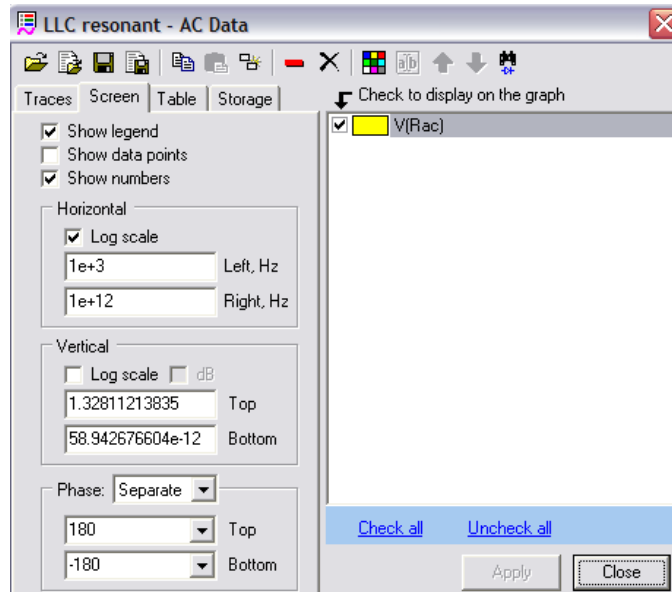
Now Select AC->Data menu and set the 'AC Data' parameters as follows:  
Add a trace to display the Voltage of the Rac resistor.

(**Hint:** Select V in left column and Rac in middle column and select the green plus symbol button with the word 'Add' to add trace )



**Figure 7 - Parameter setting for AC->Data menu**

Now select the 'Screen' tab and ensure the Vertical scale 'log' check box is unselected. To plot in voltage instead of dB.



**Figure 8 - 'Screen' to uncheck 'dB' box and have the results displayed as voltage versus dB.**

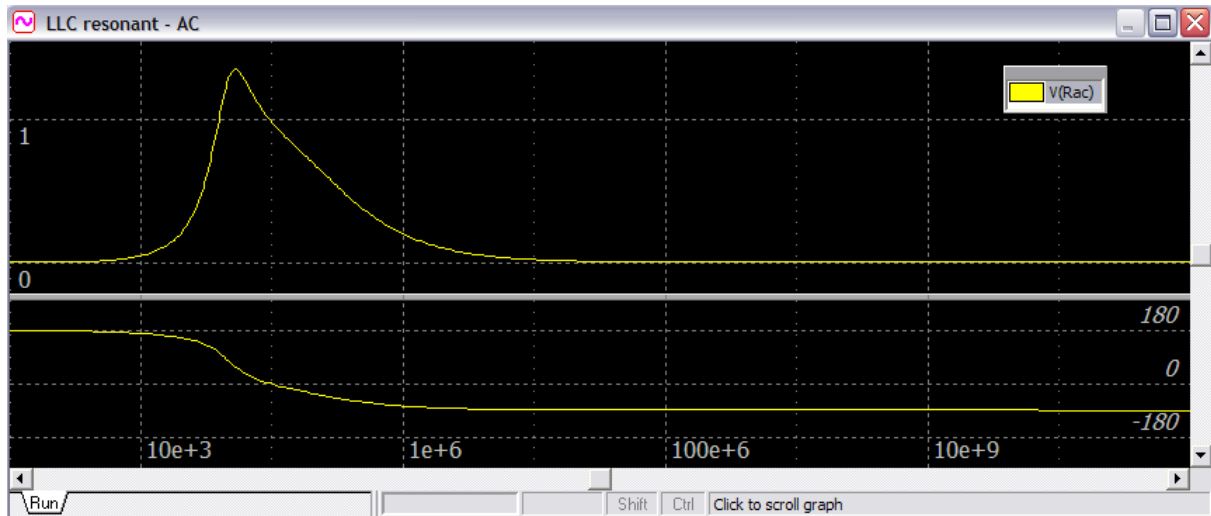


Figure 9 - Rac Output voltage response versus frequency of FHA model

- **Comment on the converters voltage output versus frequency.**
- **How does it compare to Figure 1?**
- **Is the converter a Buck? Boost? Buck-Boost?**

Now let's see how the series resonant LLC converter output voltage behaves with various loads. On the schematic, select the component that you want to sweep (Rac in this case). From the pull down menu select Tools -> Script. Select the 'sweep' tab and under the 'sweep' tab select the 'list' tab. Under 'Name' select the  $R_{ac}$  from the pull down (It should be the only one listed...) Set up the Rac resistance values for the following values: [1, 10, 100, 200, 400, 1000] Select the blue 'Run script' arrow to see the results.

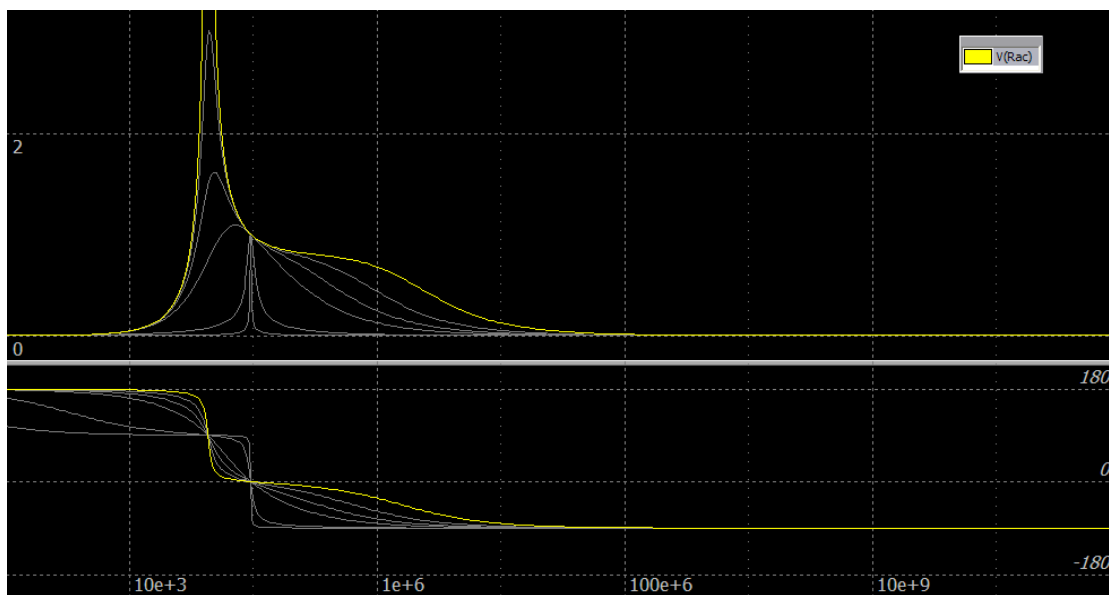


Figure 10 - LLC series resonant converter with varying load values.



- Looking at the voltage and phase response, can you identify the two separate tank circuits? (Hint: It's easiest to discern in the phase response)
- Does the load resistance affect either or both of the tanks circuits?
- Does the NL5 response match up to the typical voltage conversion ratio of a LLC resonant converter shown in the graph below?

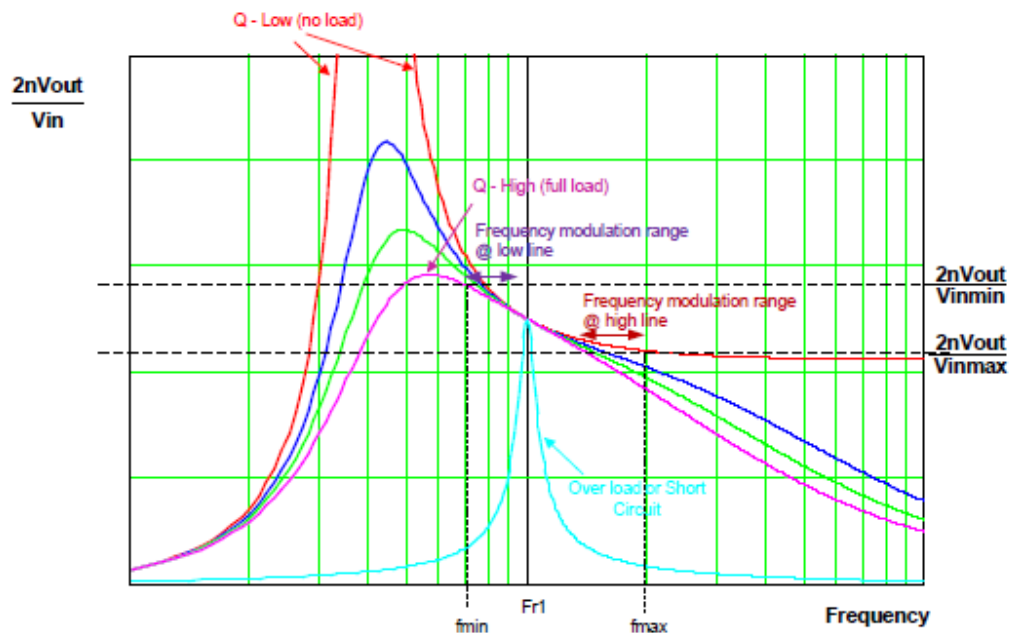
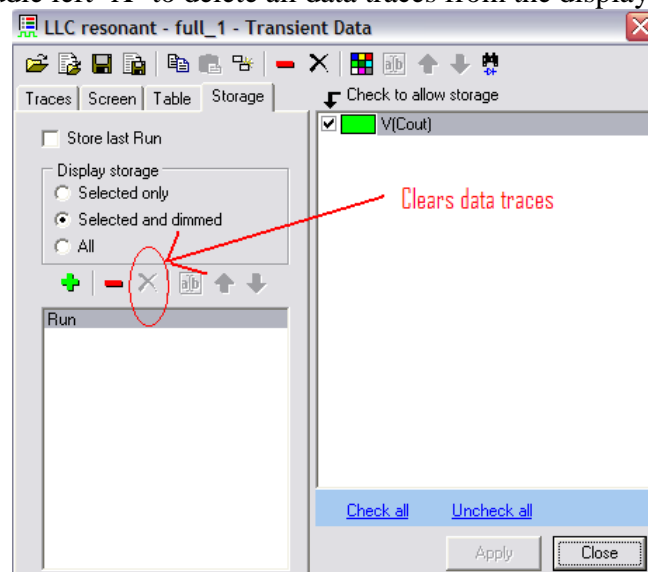


Figure 11 - Typical voltage conversion ratio of a LLC converter

**Hint:** To clear all the traces, select Transient->Data pull down menu, select the ‘storage’ tab and click on the black middle left ‘X’ to delete all data traces from the display.



Now build the full half bridge series resonant converter shown below in NL5:

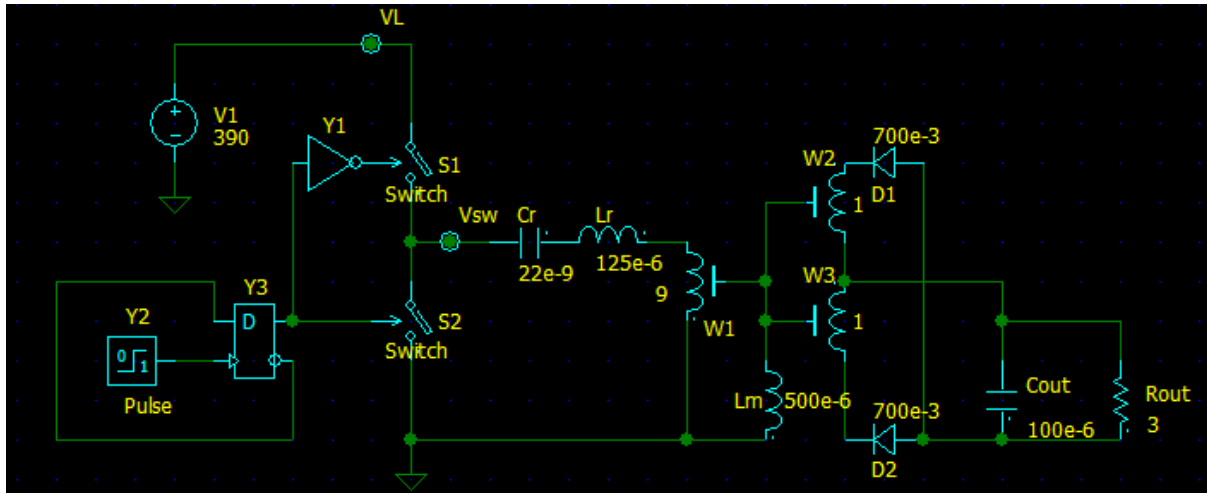


Figure 12 - Series resonant half bridge LLC converter in NL5

### Hints:

- 1) Select 'Logic generator' under the 'Y' component menu for Y2



- 2) Select 'D trigger' under the 'Y' component menu for Y3



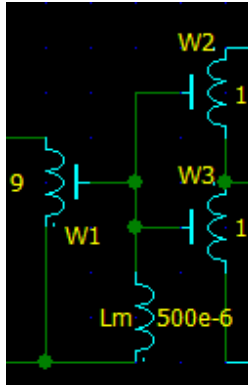
- 3) Select 'Logic-1' under 'Y' menu for inverter component Y1



- 4) The half bridge transformer must be constructed of three individual 'windings' which can be found under the 'W' component menu for {W1,W2 and W3}. Be sure to set W1 to 9 turns for the primary side of the transformer step down



- 5) Use a regular inductor for the magnetizing inductance Lm of the 'ideal' transformer that was constructed out of individual windings. Connect the 'core' pins of the windings together along with the inductor representing the magnetizing inductance of the transformer. (See NL5 manual snippet shown in Figure 13 for more information)



- 6) Set the 'parameter' of the Pulse to the following:  
 7)

Y2	Pulse
Period	90e-6
Width	1e-9
Delay	0
Active	High

- 8) Set all other components values to those shown on series resonant half bridge LLC schematic above.

Model	Parameter	Units	Description
Winding	n	turns	Number of turns.

**Winding.** The Winding is actually an ideal transformer, with 1 turn second winding, one end of each is grounded, and another end is shown as a "core" pin of the winding:

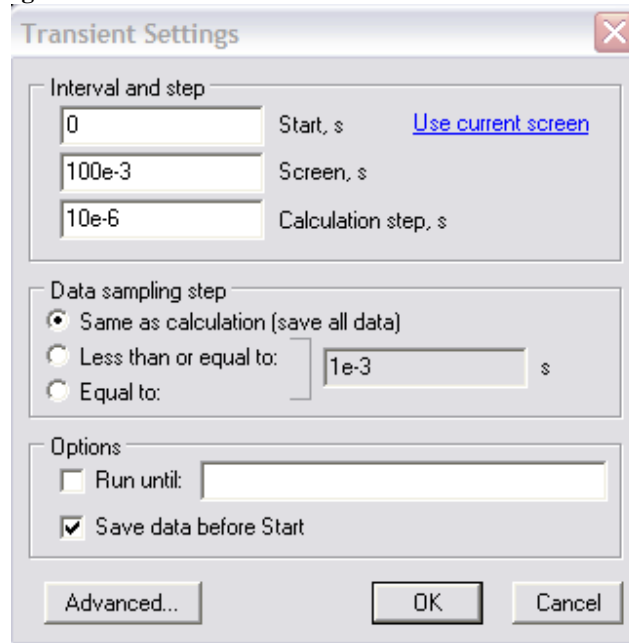
**Equivalent schematic**

To make an ideal transformer, connect cores of two or more windings by wire. Core magnetizing can be modeled by setting linear or non-linear inductor from core to ground:

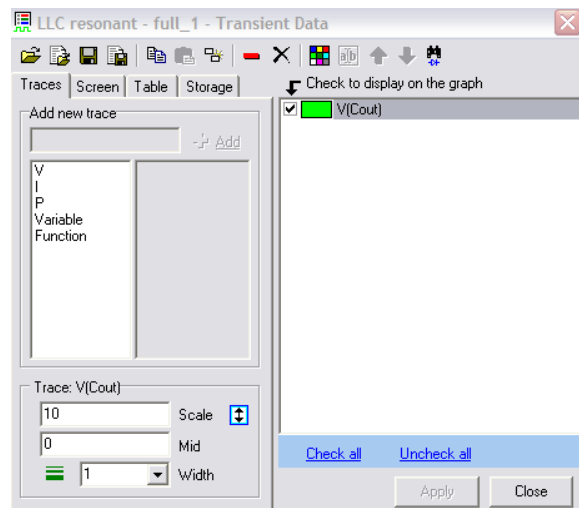
**Ideal transformers**                      **Transformer with magnetizing inductor**

Figure 13 - p378 of NL5 manual - Constructing arbitrary transformers with magnetizing inductor using the 'winding' feature

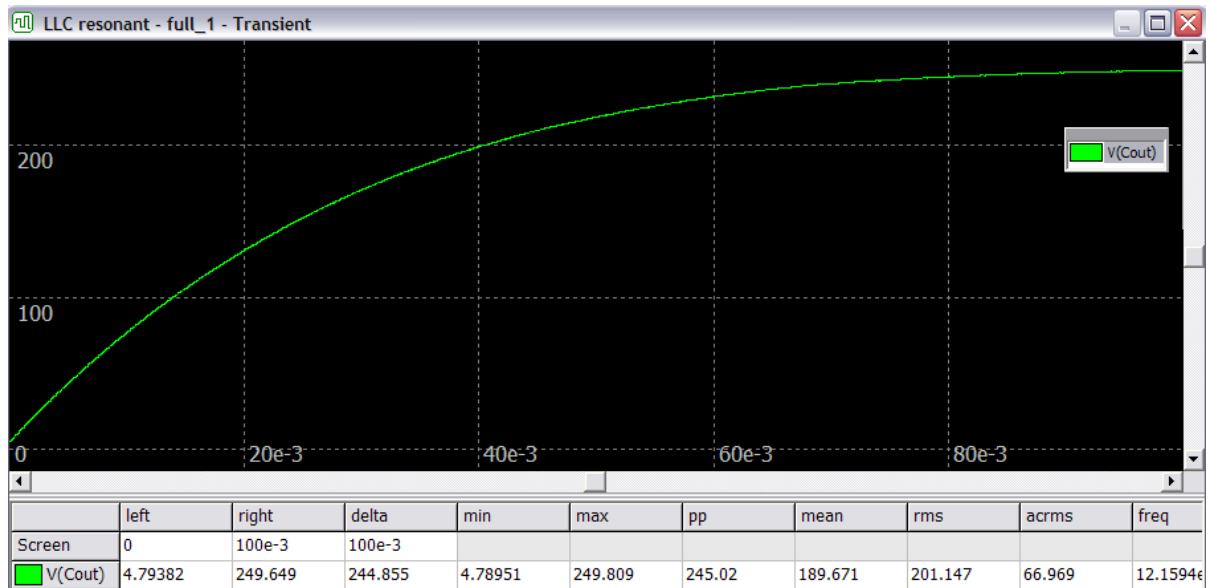
Now set the transient settings to the values shown below.



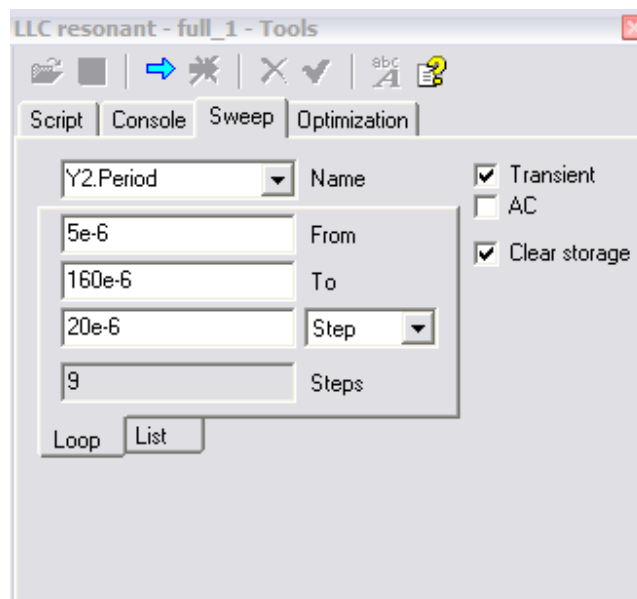
Now select Transient -> Data menu and add a new trace to plot the Voltage of component Cout.



The converter response should look similar to below:



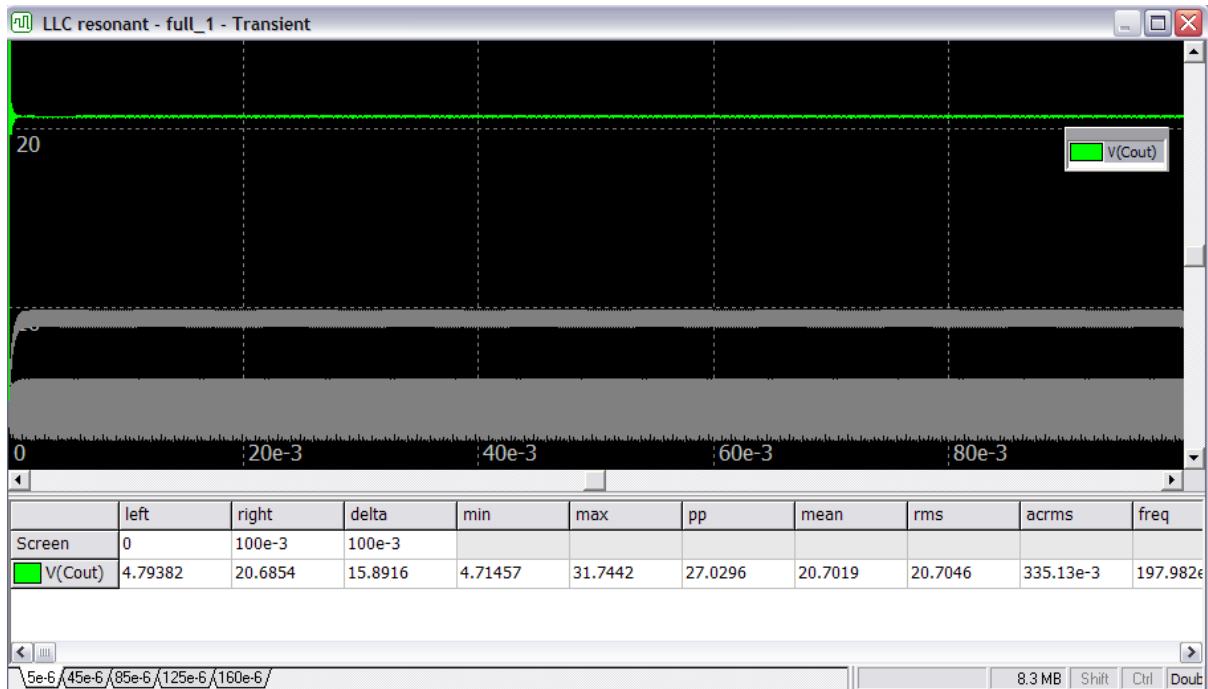
Select Tools ->Script and run LLC converter and set to run pulse period from 5us to 160 us in 20 us steps.



Press the 'Blue' arrow to start runs.

Select the different tabs at the bottom of the data display to highlight each run.

- Describe the voltage response  $M(d)$  of the converter as the period is run from 1uS to 160uS in 10uS steps. Is it as you expected?



- What can you say about the converter's frequency needed to run under (near) full load conditions? Which region {1,2 or 3} is it operating in?

Now set the pulse period for Y2 to 50uS (50e-6s) and sweep the Rac value from the 3 ohm near full load upwards to say 1000 ohms to simulate the converter becoming unloaded.

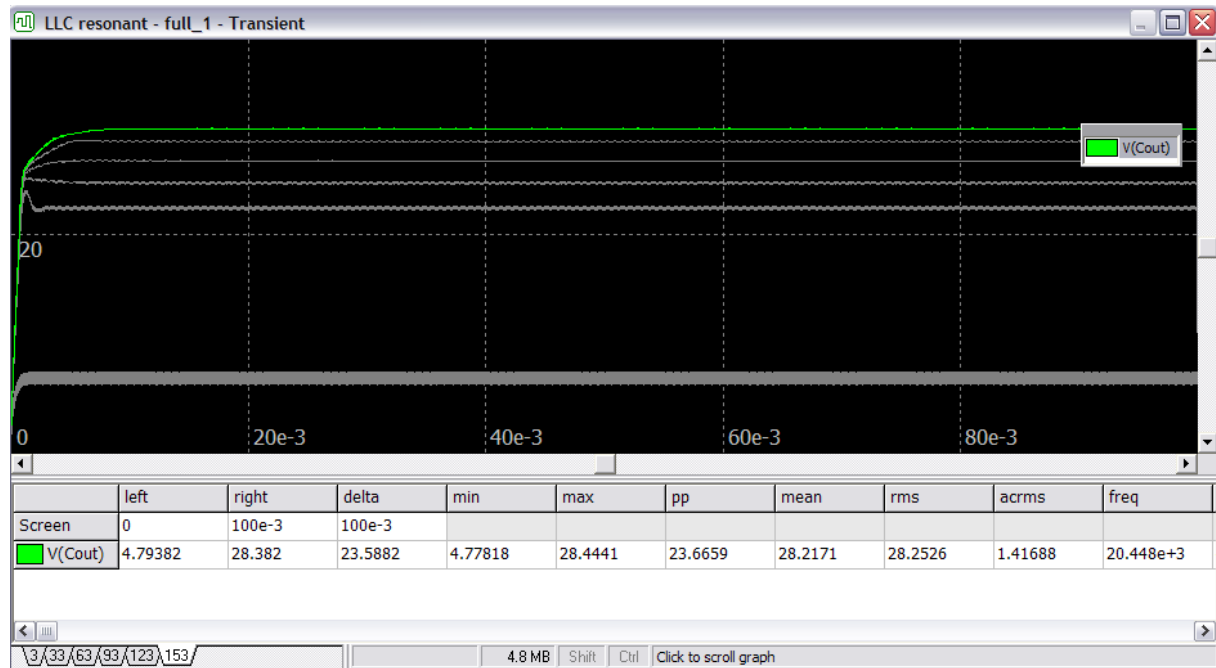


Figure 14 - Transient response of LLC converter when sweeping Rac

- What does the converter output voltage want to do with the change in load when there isn't feedback to provide regulation to the output voltage?
- What would the feedback need to adjust to maintain output voltage regulation as the load resistance increases?

## Simulation of LLC Resonant Circuit Using MATLAB<sup>®</sup>.

**NOTE:** The simulations that follow are intended to be completed with MATLAB. It is assumed that the student has a fundamental understanding of the operation of MATLAB. MATLAB provides tutorials for users that are not experienced with its functions.

### PROCEDURE:

**Part 1:** write an m file shown in figure 16.

**V<sub>m</sub>** is the variable voltage source. It is shown as Vfund(AC) in the schematic below.

**C<sub>r</sub>** is a variable ideal capacitor. Set to 22nF

**L<sub>r</sub>** is a variable inductor. Set to 125uH.

**L<sub>m</sub>** is a variable inductor. Set to 500uH.

**R** (shown as R<sub>ac</sub> below) is a variable ideal resistor. Set to 157 Ω

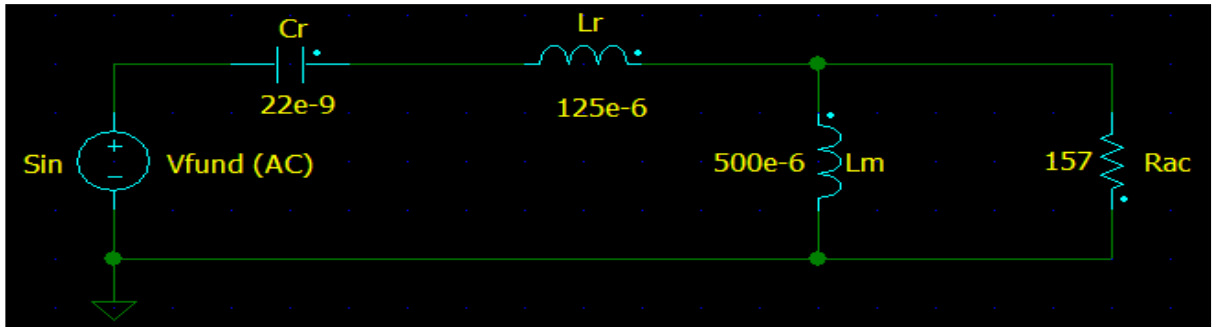


Figure 15 - Circuit to simulate using Matlab



```

%*****
% LLC Series resonant converter
% Craig Powers
% Colorado State University
% Electrical and Computer Engineering student
%*****

%define all the components values and units for Tanks
      %Units
Vm=1;      %Volts
R=157;     %ohms
Cr=22e-9;  %Farads
Lr=125e-6; %Henrys
Lm=500e-6; %Henrys

%define the input impedance
ZCr=tf([0,1],[Cr 0]);
ZLr=tf([Lr 0],[0,1]);
ZLm=tf([Lm 0],[0,1]);

% the total resistor and/or capacitor connected in parallel
Zparallel=1/(1/R+1/ZLm);
% the total resistor and/or capacitor connected in series
Zseries=ZCr+ZLr;
% the input transfer function
Zinput=Zparallel+Zseries

%The bode plot of input impedance
figure(1)
bode(Zinput)
title('input impedance of LLC tank circuit');
%calculate zero frequency , beta and Q factor of the tank

%z is zero frequency
%p is poles
%k is static gain
[z,p,k]=zpkdata(Zinput,'v')

```

### Figure 16 - Input impedance for LLC circuit

Once the above m file is captured, the simulation can be run. First, go to your directory. Find your m file and then run your file. If there is a red message on your MATLAB window, then you need to correct your error. Otherwise, you will see the solution as shown in figure 17 below.

```
Command Window
File Edit Debug Desktop Window Help

Transfer function:
8.758e-018 s^3 + 1.375e-011 s^2 + 3.185e-006 s + 1
-----
7.006e-014 s^2 + 2.2e-008 s

z =

1.0e+006 *

-1.3649
-0.1026 + 0.2704i
-0.1026 - 0.2704i

p =

0
-314000

k =

1.2500e-004
```

Figure 17 - solution for input impedance of LCC

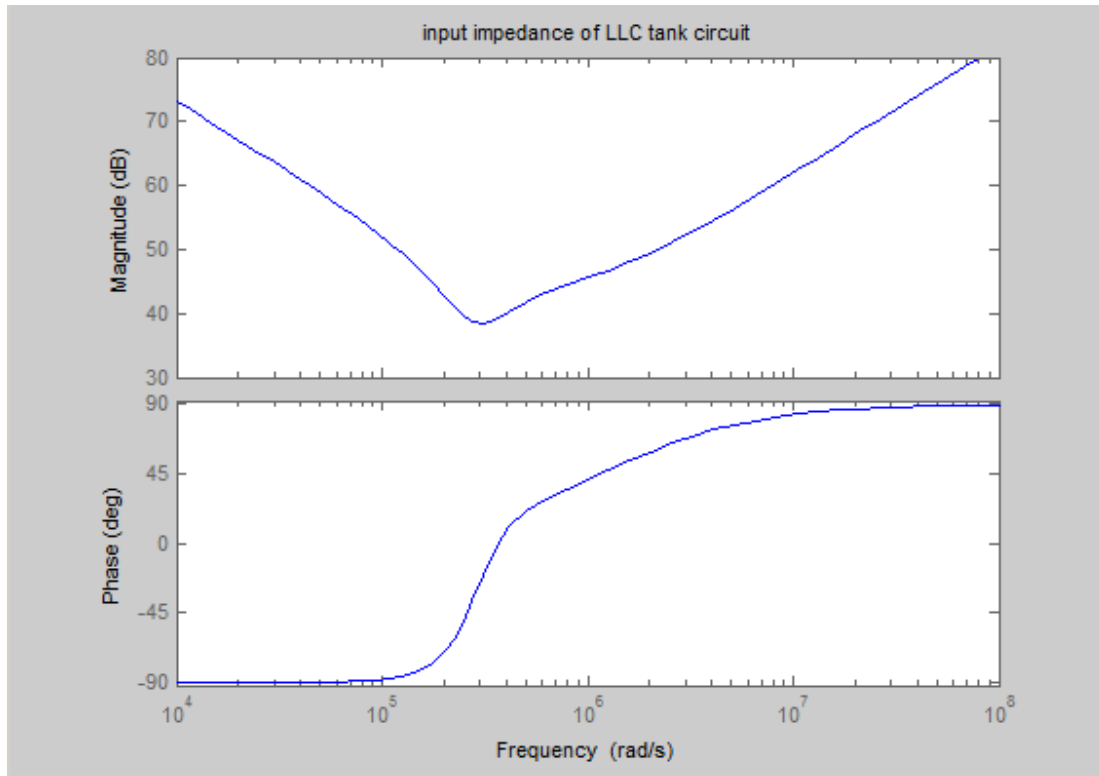


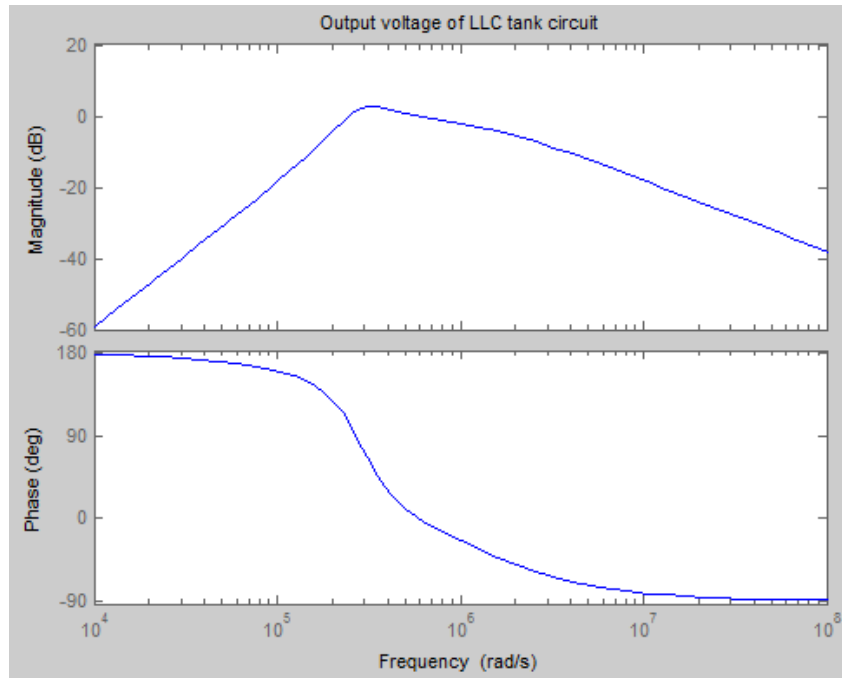
Figure 18 – Plot of the input impedance for LCC circuit

Next, plot the output voltage of the LLC circuit by adding the output voltage equation to the LLC m file. Then rerun the LLC m file.

```
%
%define the output voltage function
%
Voutput=Vm*Zparallel/(Zparallel+Zseries);
%bode plot for the output voltage
figure(2)
bode(Voutput)
% write the title of the bode plot for output voltage
title('Output voltage of LLC tank circuit')
% z is zero frequency
% p is poles
% k is static gain
[z,p,k]=zpkdata(Voutput,'v')
wn=sqrt(p(1)*p(2))
```

```
z =  
  
1.0e+005 *  
  
0  
0  
-3.1400  
  
p =  
  
1.0e+006 *  
  
-1.3649  
-0.3140  
-0.1026 + 0.2704i  
-0.1026 - 0.2704i  
  
k =  
  
1256000  
  
wn =  
  
6.5465e+005  
  
>>
```

Figure 19 - Output from output voltage Matlab code snippet above



**Figure 20 - Output voltage of LLC tank circuit**

Now plot the inductor currents of the LLC circuit by adding the inductor current equations to the LLC m file. Then rerun the LLC file.

```
%bode plot for the inductor current Lr
ILr_inductor=(Vm-Voutput)/Zseries;
figure(3)
bode(ILr_inductor)
%write the title of the bode plot for output voltage
title('Inductor Lr current of LLC tank circuit')
% z is zero frequency
% p is poles
% k is static gain
[z,p,k]=zpkdata(ILr_inductor,'v')
wn=sqrt(p(1)*p(2))
[A,B]=damp(ILr_inductor)

%bode plot for the inductor current Lm
ILm_inductor=(Voutput)/Zparallel;
figure(4)
bode(ILm_inductor)
%write the title of the bode plot for output voltage
title('Inductor Lm current of LLC tank circuit')
% z is zero frequency
% p is poles
% k is static gain
[z,p,k]=zpkdata(ILm_inductor,'v')
wn=sqrt(p(1)*p(2))
[A,B]=damp(ILm_inductor)
```

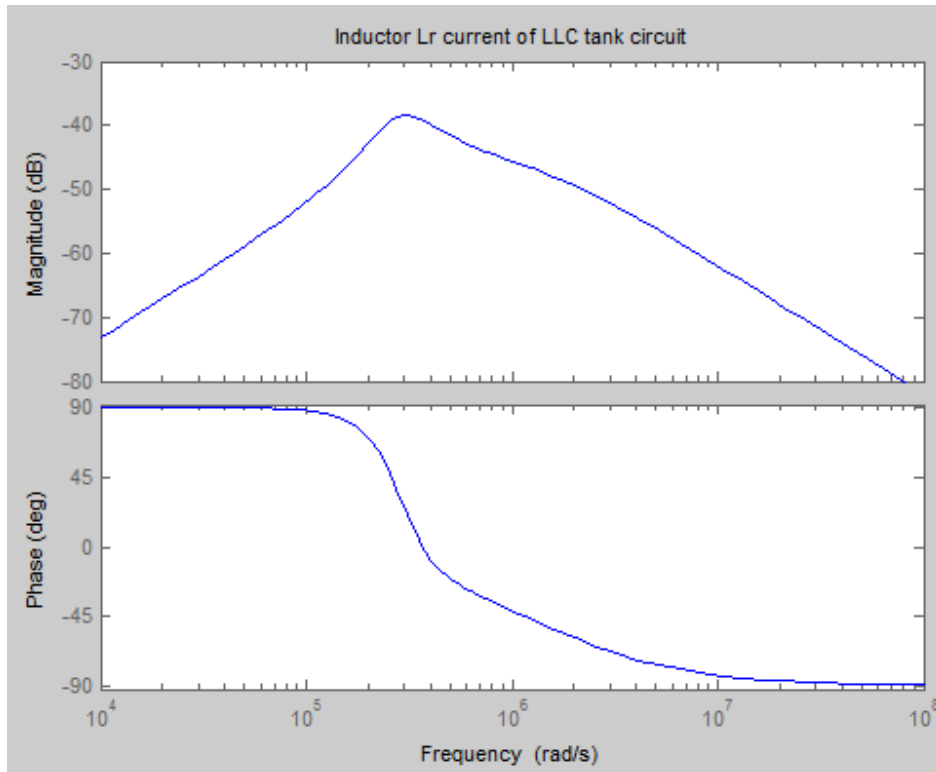


Figure 21 - Inductor Lr current

[Command window results]

z =

1.0e+005 \*

0

-0.0000 + 6.0302i

-0.0000 - 6.0302i

-3.1400 + 0.0000i

-3.1400 - 0.0000i

p =

1.0e+006 \*

-1.3649

-0.0000 + 0.6030i

-0.0000 - 0.6030i

-0.3140

-0.1026 + 0.2704i

-0.1026 - 0.2704i

k =

8.0000e+003

wn =

6.4150e+005 -6.4150e+005i

A =

1.0e+006 \*

0.2892  
0.2892  
0.3140  
0.6030  
0.6030  
1.3649

B =

0.3546  
0.3546  
1.0000  
0.0000  
0.0000  
1.0000

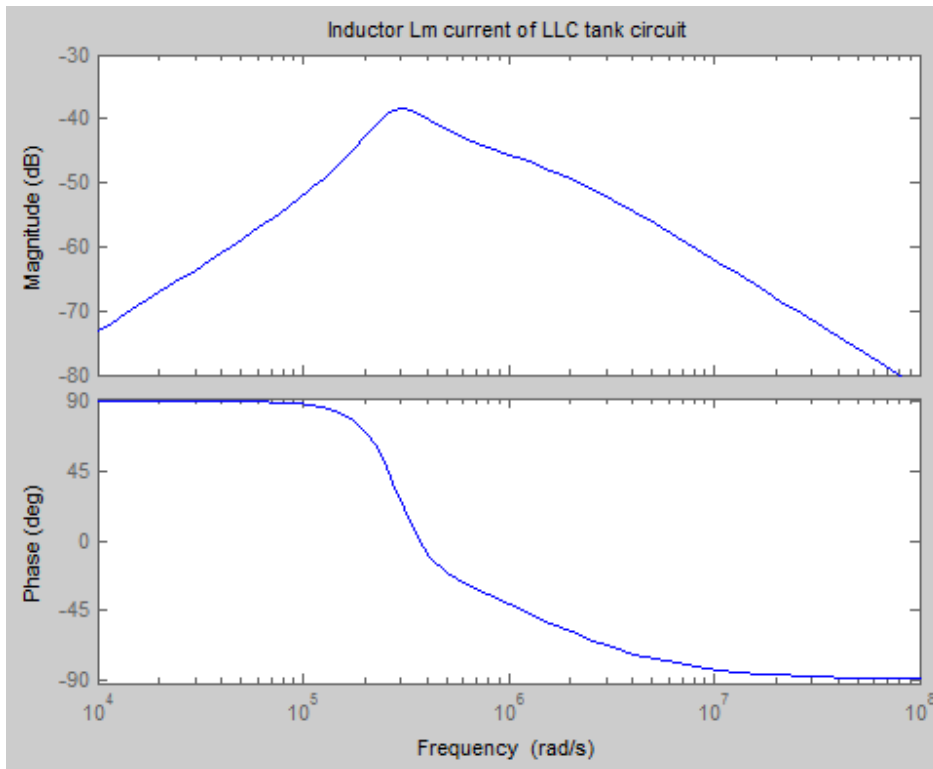


Figure 22 - Inductor Lm current

[Command window results]

z =

1.0e+005 \*

0  
0  
-3.1400  
-3.1400

p =

1.0e+006 \*

```

0
-1.3649
-0.3140
-0.1026 + 0.2704i
-0.1026 - 0.2704i

```

k =

```
8.0000e+003
```

wn =

```
0
```

A =

```
1.0e+006 *
0
0.2892
0.2892
0.3140
1.3649
```

B =

```
-1.0000
0.3546
0.3546
1.0000
1.0000
```

Now find the zero crossing for the phase of the inductor currents. First define the input impedance as a vector. Write a loop function to do the zero crossing of the phase. Then rerun the simulation. If there is any error message on your MATLAB windows, then correct your error and then rerun the simulation. Otherwise, you will see the results as shown below.

```

%
%zero cross of the phase of inductor current
%
%define input impedance as a vector
w=1e5:100:1e6;
% define interesting of w
an=size(w);
%setting for the loop up
jmax=an(2);
% now do the for loop
for i=1:jmax
    %simple impedance of each elements
    ZLr_inductor(i)=0+j*w(i)*Lr;
    ZLm_inductor(i)=0+j*w(i)*Lm;
    ZCR(i)=0-j*(1/(w(i)*Cr));
    ZR(i)=R;
    %inductor Lr connected in series with Capacitor Cr
    Zs(i)=ZLr_inductor(i)+ZCR(i);
    %Resistor connected in series with Inductor Lm
    Zp(i)=(ZLm_inductor(i)*ZR(i))/(ZLm_inductor(i)+ZR(i));
    %the output of the circuit. To find the output voltage of the

```



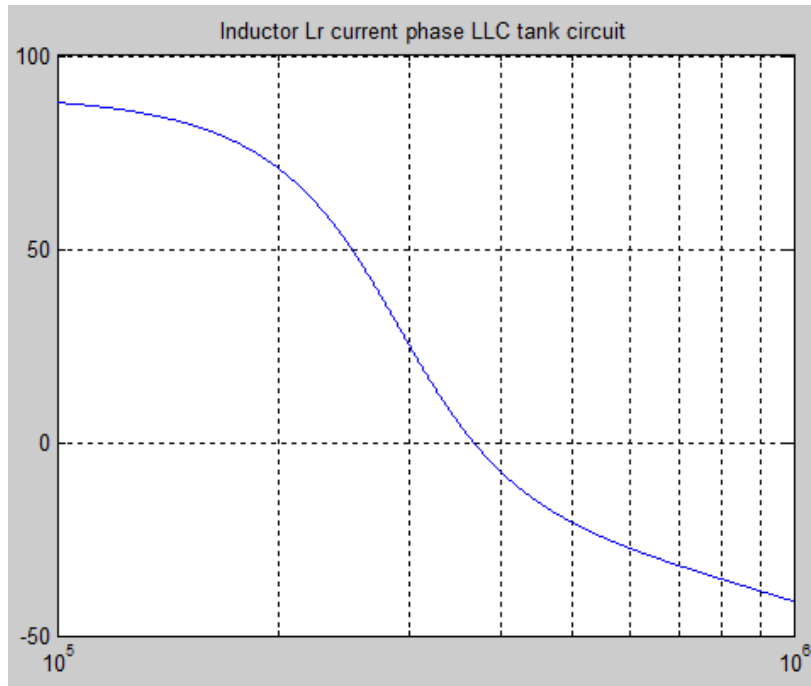
```

    %circuit using voltage divider method
    Vout(i)=Vm*Zp(i)/(Zp(i)+Zs(i));
    %inductor Lr current
    I_Lr(i)=(Vm-Vout(i))/Zs(i);
    %inductor Lm current
    I_Lm(i)=Vout(i)/ZLm_inductor(i);
end

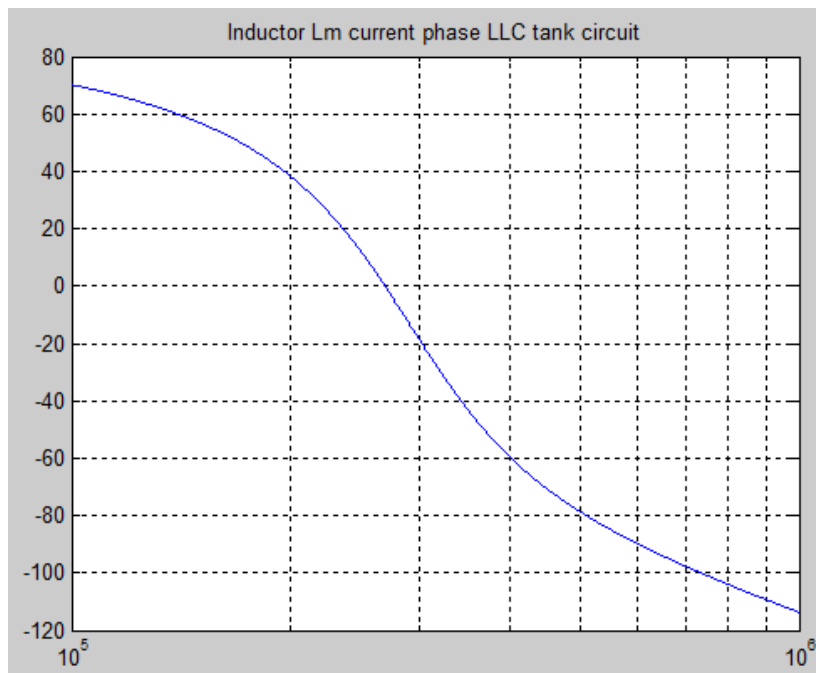
%find the resonant frequency of Lr by looking for the zero crossing points.
for i=1:jmax
    if phase(I_Lr(i))<0, x=i;
        break;
    end
end
wo=w(x-1)+(w(x)-w(x-1))/2;
%plot the inductor current in degrees
figure(5)
semilogx(w,phase(I_Lr)*180/pi)
title('Inductor Lr current phase LLC tank circuit')
grid
sprintf('the resonant frequency Lr is %d.',wo)

%find the resonant frequency of Lm by looking for the zero crossing points.
for i=1:jmax
    if phase(I_Lm(i))<0, x=i;
        break;
    end
end
wo=w(x-1)+(w(x)-w(x-1))/2;
%plot the inductor current in degrees
figure(6)
semilogx(w,phase(I_Lm)*180/pi)
title('Inductor Lm current phase LLC tank circuit')
grid
sprintf('the resonant frequency Lm is %d.',wo)

```



**Figure 23 - Inductor Lr Current Phase**



**Figure 24 - Inductor Lm Current Phase**

ans =

the resonant frequency Lr is 367950.

ans =

the resonant frequency Lm is 269650.

Now calculate and plot the output power of the LLC circuit by adding the output power equations to the LLC m file. The output power is a vector function, so the input impedances must again be defined as a vector. Write a loop function to do the zero crossing of the phase. Then rerun the LLC m file. If there is any error message on your Matlab windows, then correct your error and then rerun the simulation. Otherwise, you will see the results as shown below.

```

%
%Calculate the output power of LLC circuit
%
%define input impedance as a vector
w=1e5:1000:1e7;
%define interesting points of w
an=size(w);
%setting for the loop up
jmax=an(2);

%now do the for loop
for i=1:jmax
    %simple impedance of each elements
    ZLr_inductor(i)=0+j*w(i)*Lr;
    ZLm_inductor(i)=0+j*w(i)*Lm;
    ZCR(i)=0-j*(1/(w(i)*Cr));
    ZR(i)=R;
    %inductor Lr connected in series with Capacitor Cr
    Zs(i)=ZLr_inductor(i)+ZCR(i);
    %Resistor connected in series with Inductor Lm
    Zp(i)=(ZLm_inductor(i)*ZR(i))/(ZLm_inductor(i)+ZR(i));
    %the output of the circuit. To find the output voltage of the
    %circuit using voltage divider method
    Vout(i)=Vm*Zp(i)/(Zp(i)+Zs(i));
    % output power
    P(i) = (Vout(i))^2/Zp(i);
end

%plot the output power
max(abs(P))
figure(8)
semilogx(w,abs(P))
title('Output power of LLC tank circuit')
grid

```

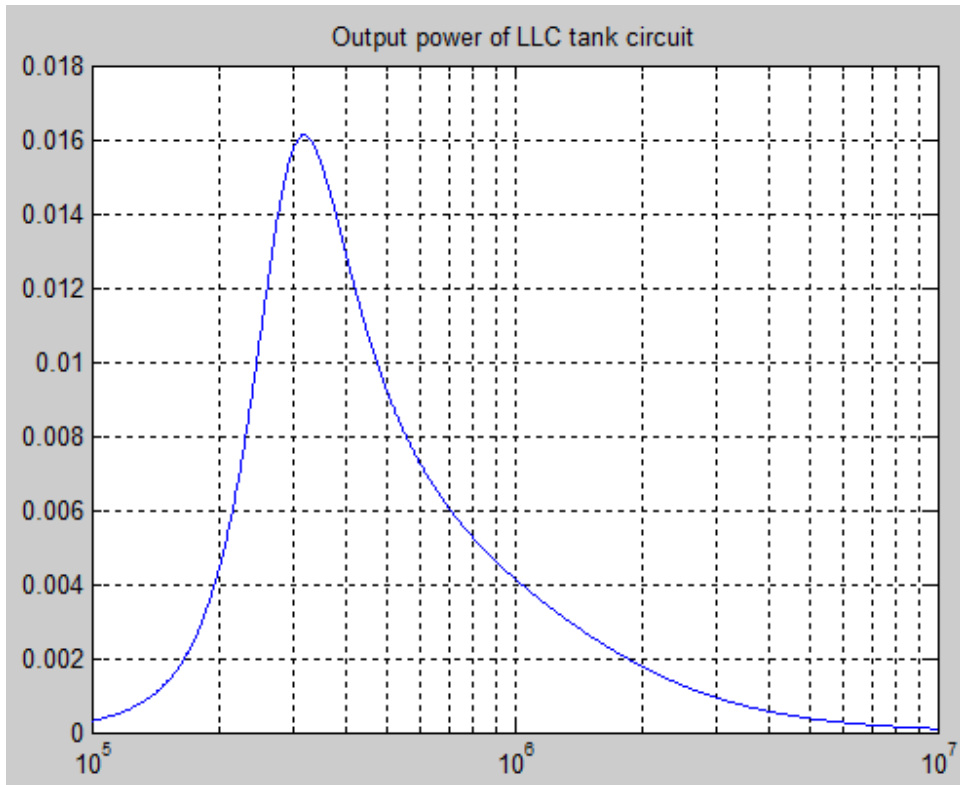


Figure 25 - output power of the LLC tank circuit

ans =

0.0161