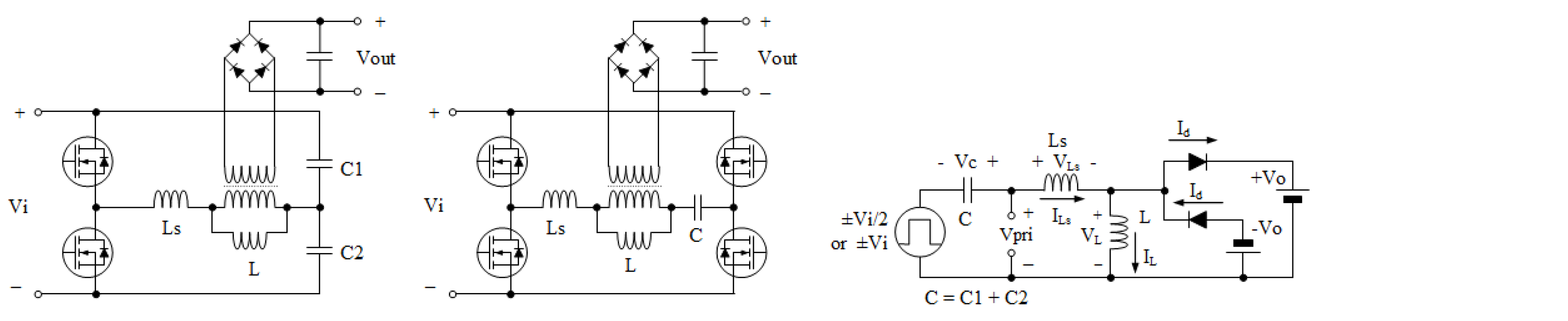
LLC converter design worksheet



Basic half bridge LLC | Basic full bridge LLC | LLC model

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Input data for LLC converter

```
L        = 344e-6      # [H]  Parallel resonance inductor (main inductance)
Ls       = 172e-6      # [H]  Series resonance inductor (leakage)
ALratio  = 1           #      Main inductance pr. turn^2 ratio ALpri/ALsec
C        = 2 * 15e-9   # [F]  Resonance capacitor
inductor = '---'       #      For external inductor type 'ext'. Otherwise Ls is integrated in the transformer
topology = '----'      #      For full bridge LLC type 'full'. Otherwise half bridge

Vo    = 196            # [V]  Ficticious output voltage in model with no transformer
Vout  = 24             # [V]  Real output voltage
Vmin  = 260            # [V]  Minimum input voltage
Vmax  = 460            # [V]  Maximum input voltage
Pmax  = 500            # [W]  Max. power in plots
```

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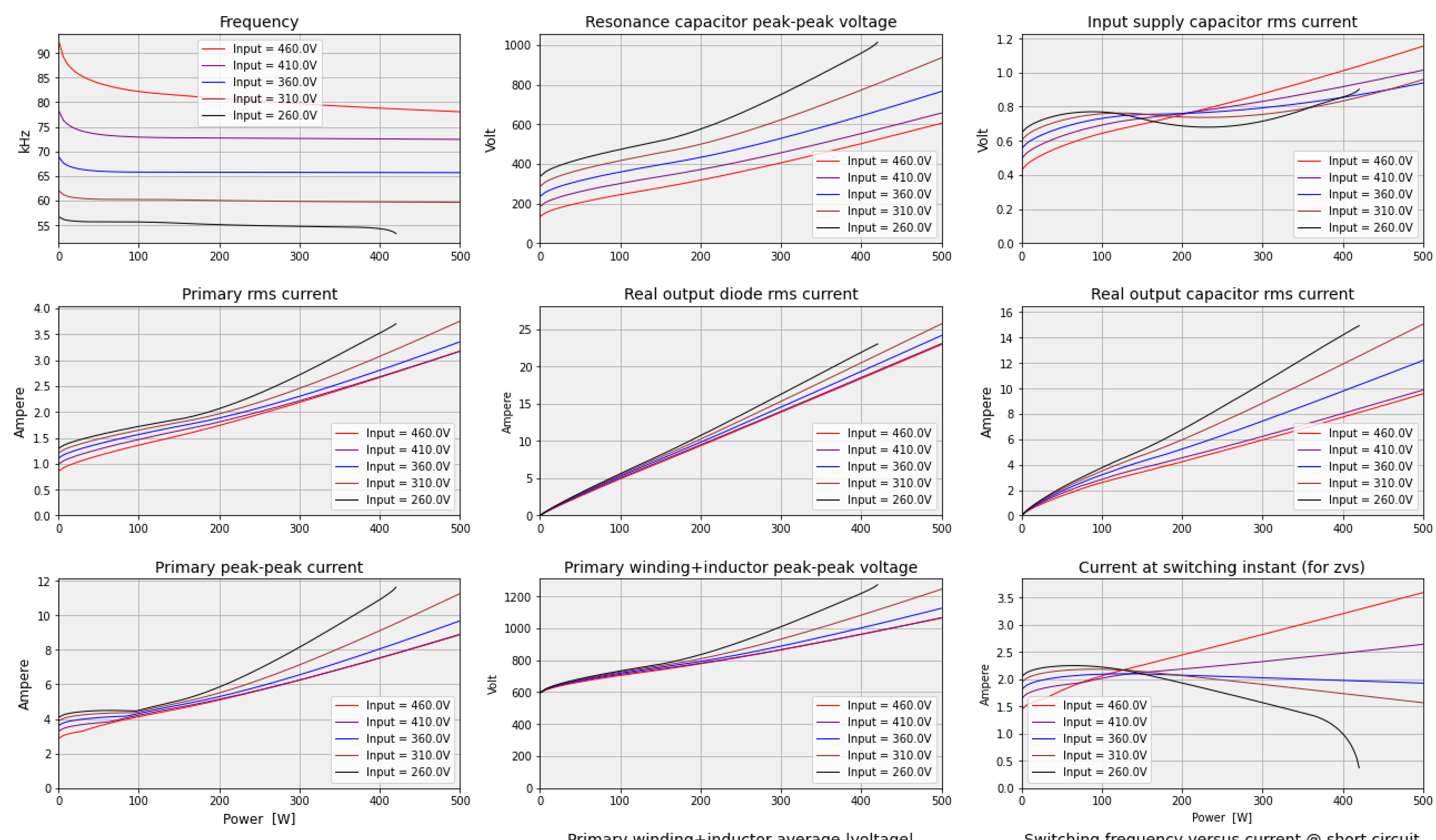
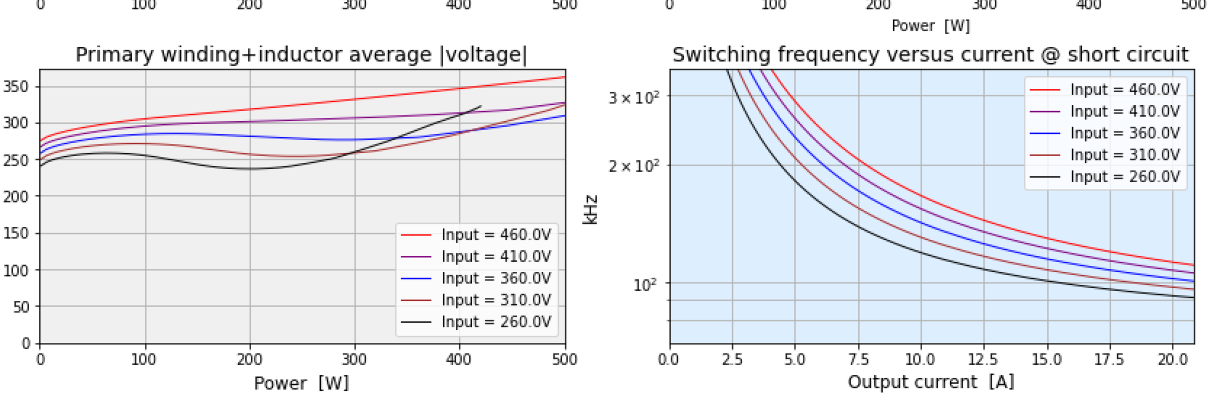


Load Independent Point 70.1 kHz
Input voltage at LIP 392.0 V

Transformer data:

Primary inductance 516.0 uH
Primary leak inductance 172.0 uH
Coupling coefficient 0.816
Turns ratio P/S 10.00



Input data for scope plots

```
power = 420    # [W]
Vin   = 260    # [V]
```

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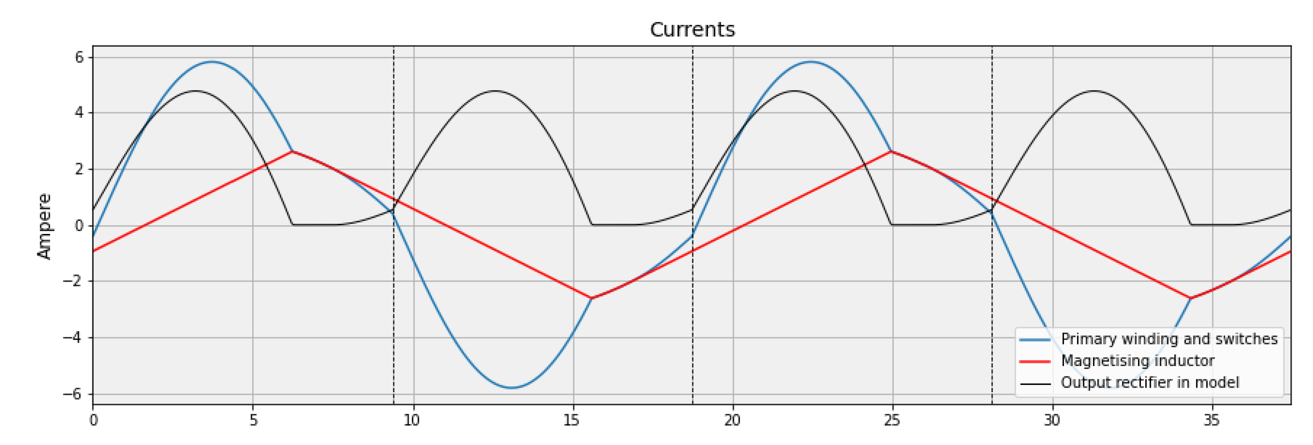


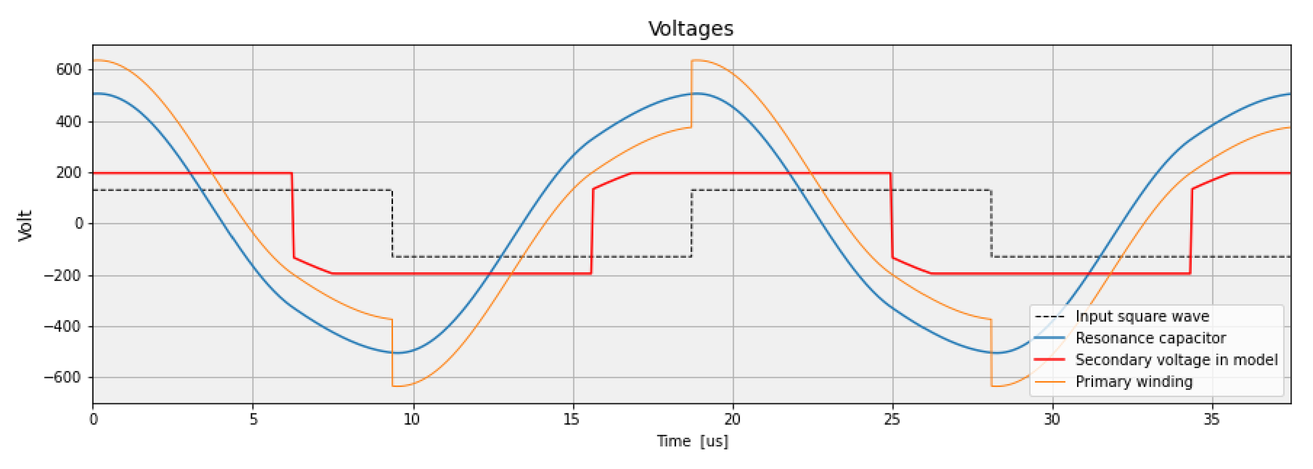
Waveform data:

Frequency 53.4 kHz

Primary current 3.7 A rms
Primary current 11.6 A pp
Secondary current 23.0 A rms
Out-capacitor current 14.9 A rms

Capacitor AC voltage 1011 V pp

Mode 3



Iteration counters
i = 6 mode 1
j = 16 mode 2
k = 22 mode 3 + 4
l = 0 mode 5 + 6

Transformer data input

```
Afe     = 125e-6     # [m^2]   Core cross section
volfe   = 11.5       # [cm^3]  Core volume
fe      = 2          #         Ferrite type: 1: 3C90   2: 3C95   3: 3F3 from ferroxcube
Øpri    = 20         # [mm]    Average diameter of primary winding
Øsec    = 20         # [mm]    Average diameter of secondary winding
Øpwire  = 0.05       # [mm]    Diameter primary wire
Øswire  = 0.05       # [mm]    Diameter secondary wire
parpri  = 225        #         Parallel wires in primary litz
parsec  = 1260       #         Parallel wires in secondary litz
temp    = 100        # [deg.C] Winding temperature

Np      = 50         #         Primary turns number (must give leakage inductance = Ls as defined above)
plotmax = 3          # [W]     Max power in power plots. Auto-scale is confusing
```

ETD39. Bobbin = LLC type: Pin Yue nr. PY-3902 + cover nr. PY-3902-1 or equivalent. Primary in narrow slot.

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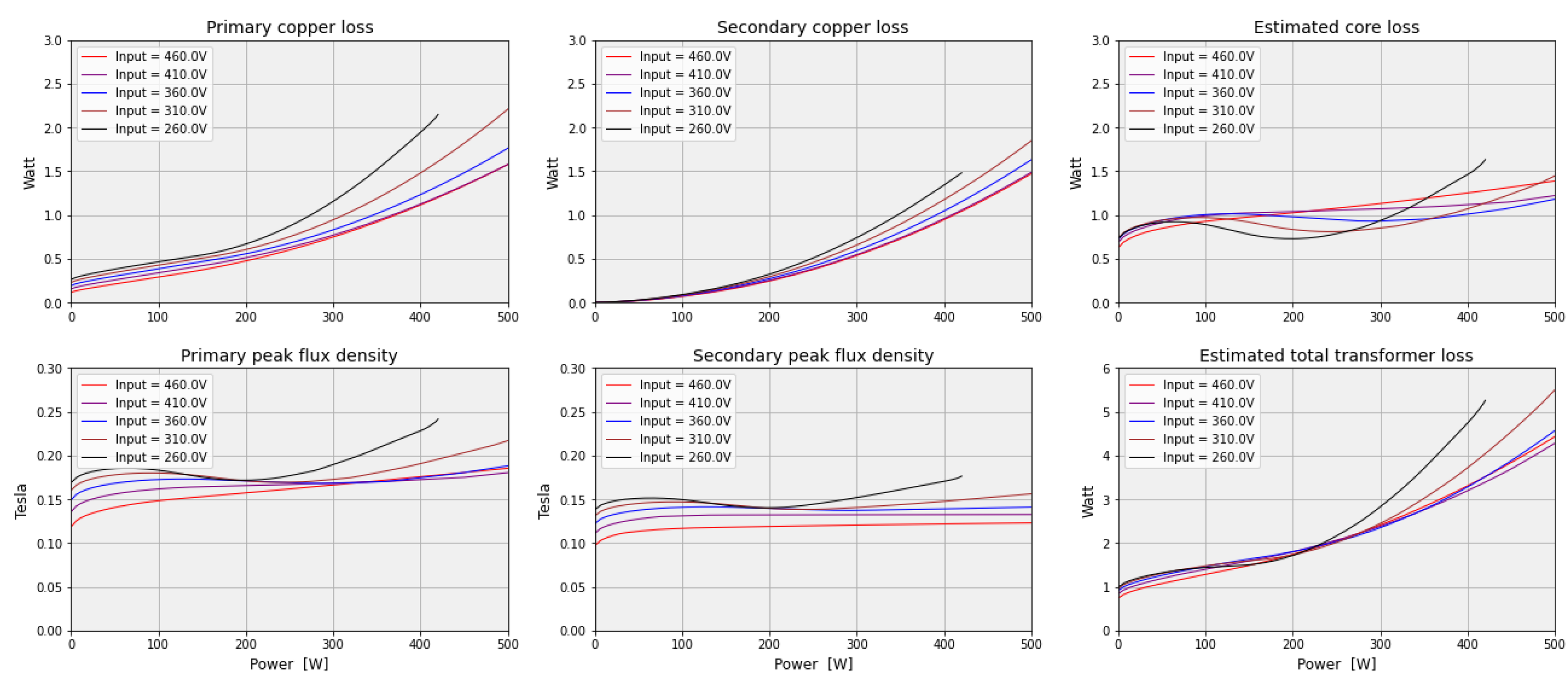
Transformer primary turns 50.0
Transformer secondary turns 5.0
Transformer air gap 0.92 mm

Primary copper resistance 0.16 Ω
Secondary copper resistance 0.003 Ω



External inductor data input

```
ALs     = 120e-6     # [m^2]   Ferrite cross section area
volLs   = 6.53       # [cm^3]  Ferrite volume
feLs    = 1          #         Ferrite type: 1: 3C90   2: 3C95   3: 3F3 from ferroxcube
templs  = 100        # [deg.C] Winding temperature
ØLs     = 16         # [mm]    Winding average diameter
ØLswire = 0.1        # [mm]    Wire diameter
parLs   = 100        #         Parallel wires in inductor winding

NLs     = 45         #         Turns number
plotmax = 3          # [W]     Max power in power plots. Auto-scale is confusing
```

Your notes and comments here: Inductor size, special requirements, etc.

Results are plotted only if "inductor = 'ext' " is selected.

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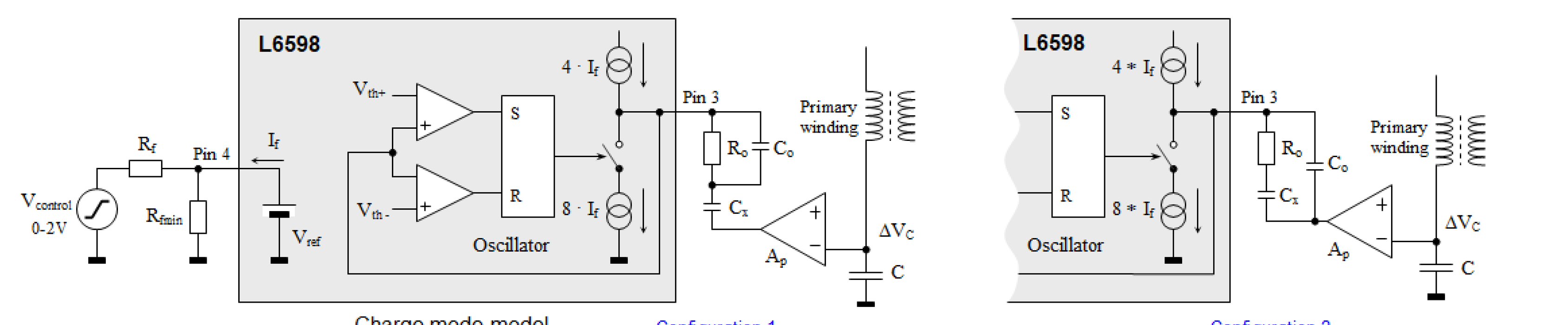
Charge mode application with L6598

Design of control graphs for regulation loop linearity



Charge mode model | Configuration 1 | Configuration 2

```
confi = 2           #        RC configuration - see above
Co    = 220e-12     # [F]    Oscillator capacitor
Ro    = 6800        # [ohm]  Resistor in RC network
Cx    = 1           # [F]    DC blocking capacitor
Rfmin = 220e3       # [ohm]  Start-up resistor
Rf    = 39e3        # [ohm]  Frequency programming resistor
Ap    = 0.0023      #        Charge signal inverter gain
```

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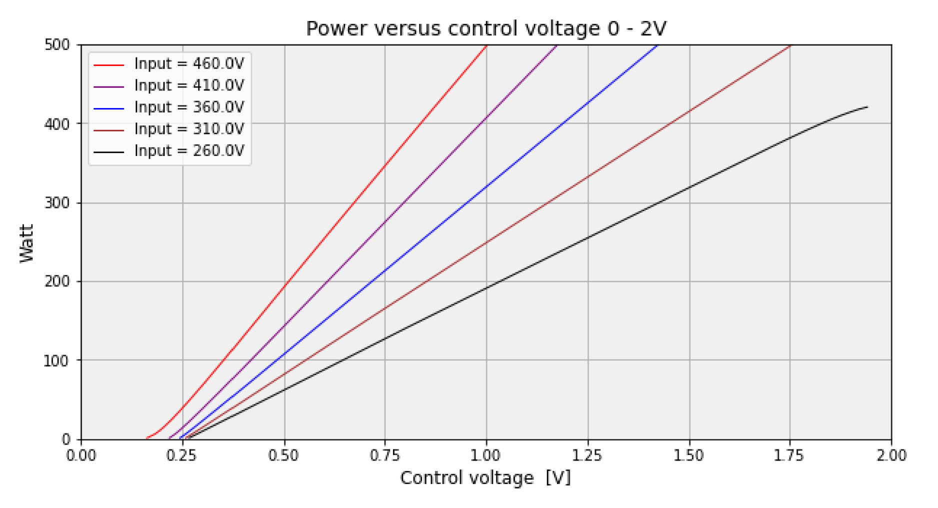

Service plots - mostly for debugging

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User guide

This worksheet is an analysis tool intended to let you see how a given set of component data in an LLC converter will work in steady state. By manipulating component data, an LLC can be optimized, but it still requires some engineering skills to know where to look for the optimum.
In contrary to the usual First Harmonic Approximation, this worksheet is based on accurate voltage and current waveforms in time. It can handle LLC converters with "leakage inductance" either integrated in the transformer or as an external inductor. For both cases it can handle the half bridge or the full bridge LLC topology.

The worksheet is organized in five sections. Each section has its own cell for input data:

1. Basic LLC design with overview plots. Here you select integrated or external inductor, half- or full bridge.
2. See a scope plot for any operating condition for the selected LLC network
3. Transformer design
4. External inductor design if external inductor was selected
5. Control graph design with the L6598 controller

The five sections must be filled in and run sequentially. The first section takes som seconds to run. If you are working in one of the subsequent sections, you can save time and annoyance by not re-running all from the start: Choose "Run Selected Cell and All Below" in the Run menu. A handy shortcut can be created for that in JupyterLab.

Choosing C, L, Ls, and Vo

The half- or full bridge is analyzed in an equivalent model with no transformer, see first picture. Here Vo is a fictitious output voltage which can be selected arbitrarily. If selected too high, it is difficult to transfer high power. If selected too low, rms currents become too high, and output voltage cannot be controlled at low power. A good starting point is to set $Vo = 0,95 * Vmax/2$.
The ratio between the fictitious Vo and the real Vout determines the turns ratio in the transformer.
The magnetizing inductance L can be set with an air gap in the transformer core. The "leakage inductance" Ls can be either integrated in the transformer by physically separating primary and secondary windings, or it can be an external inductor connected in front of a transformer with "good" magnetic coupling.
For narrow input- and output voltage ranges, a good starting point is to choose resonance frequency $foo = \frac{1}{2*\pi*\sqrt{Ls*C}} = 50 - 100kHz$.
Then calculate $A = 0.3\frac{Vmin^2}{Pmax}$ (unit for A is Ω) and choose $C = \frac{1}{2*\pi*A*foo}$ and $Ls = \frac{A}{2*\pi*foo}$.
Magnetizing inductance: start with $L = 4 * Ls$.
Higher L may jeopardize zero-volt switching at some working conditions - see plot "Current at switching instant (for zvs)". Lower L will cause higher losses due to larger magnetizing current - see plot "Primary rms current".
For wider input or output voltage range you may have to decrease L and accept higher losses.

Scaling

For any LLC design you can achieve a new equivalent design intended for another power, input voltage, or frequency by scaling.

Power scaling:	$Ls_{new} = Ls * \frac{P}{P_{new}}$	$L_{new} = L * \frac{P}{P_{new}}$	$C_{new} = C * \frac{P_{new}}{P}$	$Vo_{new} = Vo$
Input voltage scaling:	$Ls_{new} = Ls * \left(\frac{Vi_{new}}{Vi}\right)^2$	$L_{new} = L * \left(\frac{Vi_{new}}{Vi}\right)^2$	$C_{new} = C * \left(\frac{Vi}{Vi_{new}}\right)^2$	$Vo_{new} = Vo * \frac{Vi_{new}}{Vi}$
Frequency scaling:	$Ls_{new} = Ls * \frac{f}{f_{new}}$	$L_{new} = L * \frac{f}{f_{new}}$	$C_{new} = C * \frac{f}{f_{new}}$	$Vo_{new} = Vo$

Interpreting plots

In all plots (except the scope plots) you may see end-points of some of the five curves. The end-points represent the highest possible power that can be transferred. It also represents the limit to loss of zero-volt switching. If you don't see the end points, choose a higher Pmax to see where they are. Above the "Load Independent Point" the transferrable power is in principle infinite.
If the lowest end-point is at higher power than necessary it may be advantageous to reduce the available power by power scaling, and vice versa.
Frequency span over input voltages will be reduced by selecting a lower L at the cost of a higher primary rms currents.
Primary rms current will directly influence the power loss in the two (or four) switches and in primary copper wire.
Output diode- and capacitor rms current will influence the power loss in secondary wire, rectifiers, and output DC capacitor.

Primary peak-peak current - this plot is useful if you want to use the peak current for current limiting. You can see what variations you should expect.
Primary winding+inductor peak-peak voltage is useful with inductor integrated in the transformer if you want to insert a winding in the primary part to generate an aux. supply voltage. You see what variations you should expect. Also, you must know the peak-peak voltage to design adequate insulation in the primary winding.
Primary winding+inductor average numerical volt is useful if you rectify the voltage from the same aux winding with a large enough inductor in the output of a bridge aux. rectifier. An aux. voltage rectified with this method may show less variation than a peak rectified voltage. Compare the two methods and pick the one you like best.

Current at switching instant (for zvs): Here you see how much primary current is left at the switching instant. If this current becomes too small, it will be difficult to achieve zero-voltage switching.

Switching frequency versus current @ short circuit - here you see how much you must increase frequency versus output current, if you want to run the LLC with a shorted output. This also applies at the beginning of start-up.

Transformer with integrated resonance inductor

An external resonance inductor can be necessary due to space restrictions. It may also be the best option if you want two or more output voltages which must track each other well.
Design with external inductor is straight forward. Design with integrated inductor is not so straight.
For the transformer structure you want to test, you must initially find the leakage A_L value for that structure. Make a test transformer with any turns number n of litz wire in the primary and secondary winding spaces, short one side, measure leakage inductance L_{leak} into the other side at 100kHz. Calculate $A_{Lleak} = \frac{L_{leak}}{n^2}$. Write down your result for future LLC converters.
With the Ls-value chosen above, now you directly calculate your primary turns number as $Np = \sqrt{\frac{Ls}{A_{Lleak}}}$. Is secondary turns number Ns a integer number? Probably not. Select another Np until you hit Ns = integer. Now go back to the top and adjust leakage inductance to $Ls = A_{Lleak} * Np^2$. Also adjust L with the same factor - otherwise you are heading for one more iteration, because Ns changes again when you change the ratio Ls/L.

Now fill in the transformer data for your intended transformer type. Choose wire dimensions to fill out your winding space best possible.
Observe the power loss and magentization plots. Does power loss look reasonably small and well distributed between windings and core? If wire loss is dominating, you should try to reduce Np to get the next lower Ns, and re-adjust Ls and L accordingly. Remember to adjust wire data for more copper cross section because there are fewer turns to fill the winding space.
Be prepared for an iterative process with many steps on your computer before you build your first real transformer. Also be ready to experiment with the ratio Ls/L and Vo, especially if you are trying to make a "medium-range" LLC converter. A "wide range" LLC is generally not recommended unless you are allowed to transfer less power at low input voltage.

The number "ALratio" in the "Input data for LLC converter" cell is the ratio A_{Lp} / A_{Ls} for the primary and the secondary respectively, where $A_L = \frac{inductance}{N^2}$ measured with other windings open. This ratio is usually = 1 but it can differ from 1 in cases where the magnetic structure is asymmetrical. For instance if you put primary on one side of an "UU"-structure and secondary on the opposite side, and put the air gap only in the primary side.