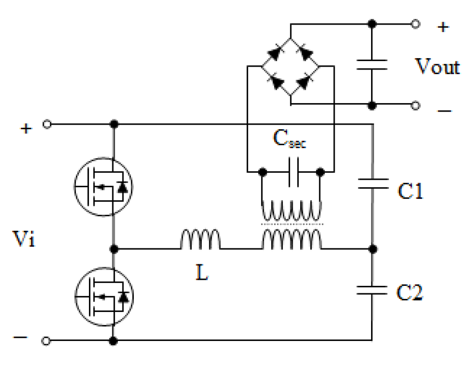
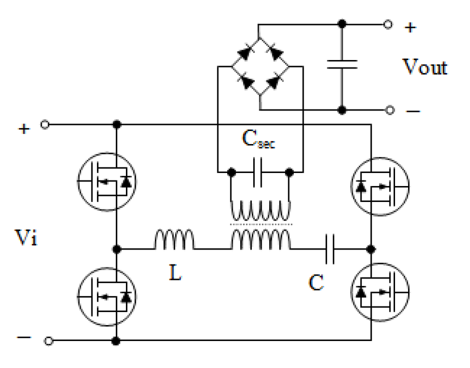
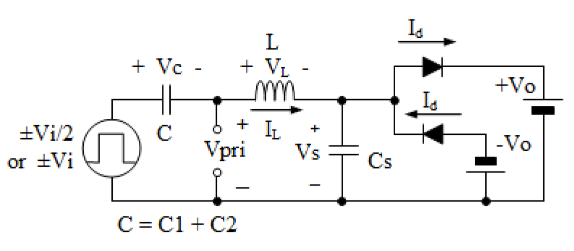
LCC converter design worksheet



Basic half bridge LCC



Basic full bridge LCC



LCC model

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Input data for LCC converter

```
L        = 240e-6      # [H]  Parallel resonance inductor (main inductance)
C        = 2 * 10e-9   # [F]  Series resonance inductor (leakage)
Cs       = 4.55e-9     # [F]  Secondary resonance capacitor in LCC model
inductor = '---'       #      For external inductor type 'ext'. Otherwise Ls is integrated in the transformer
topology = '----'      #      For full bridge LLC type 'full'. Otherwise half bridge

Vo    = 138            # [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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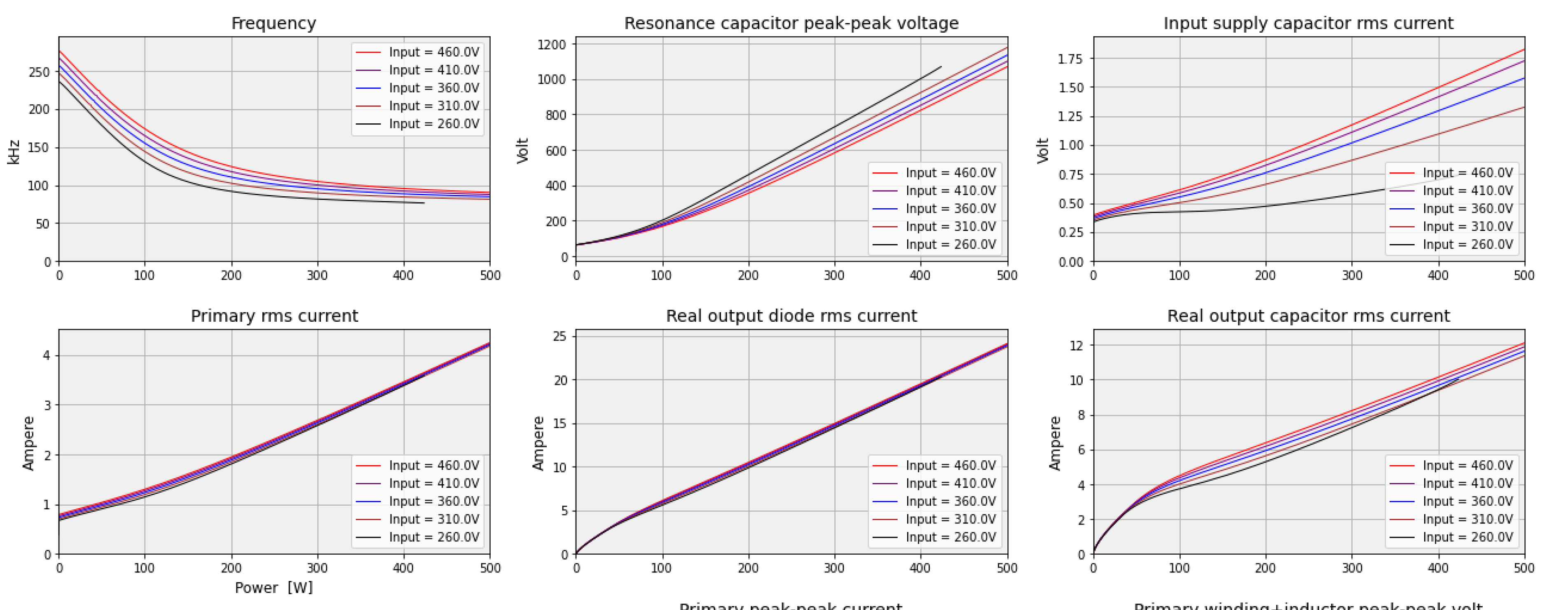
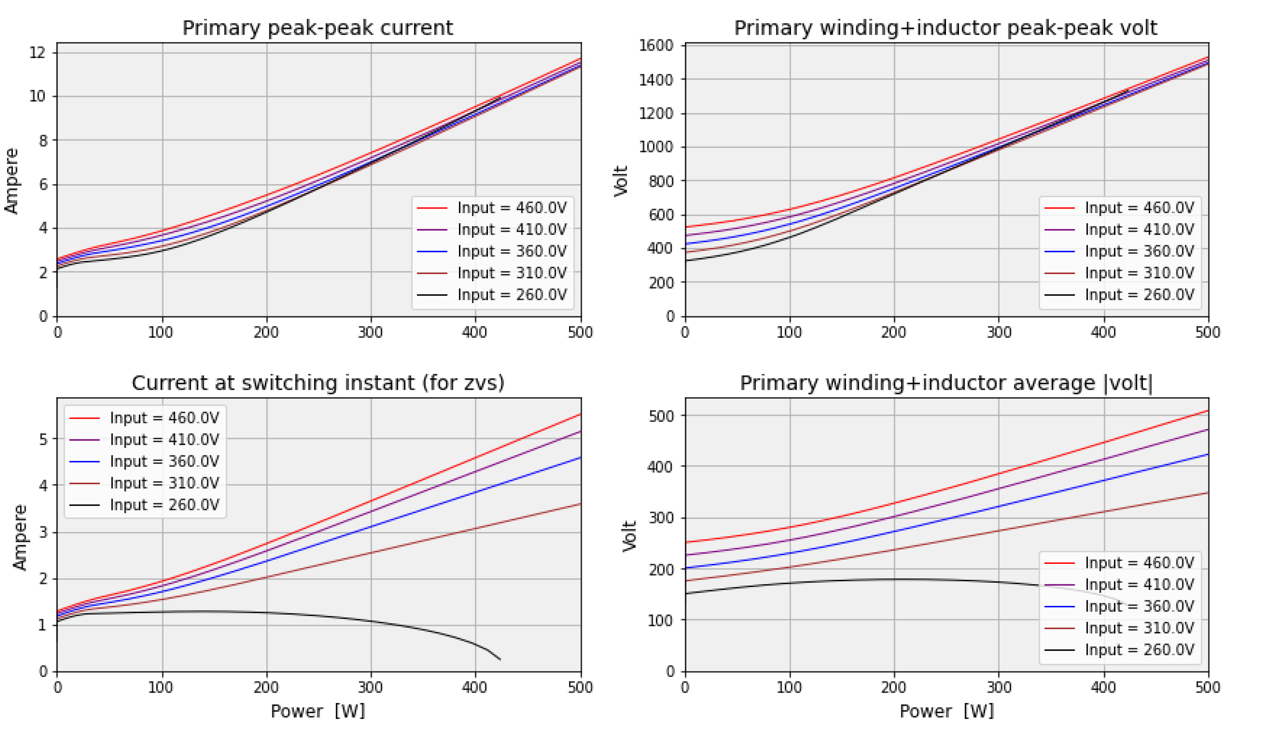


Real secondary resonance capacitor Csec = 150.4 nF



Input data for scope plots

```
Power = 410    # [W]
Vin   = 260    # [V]
```

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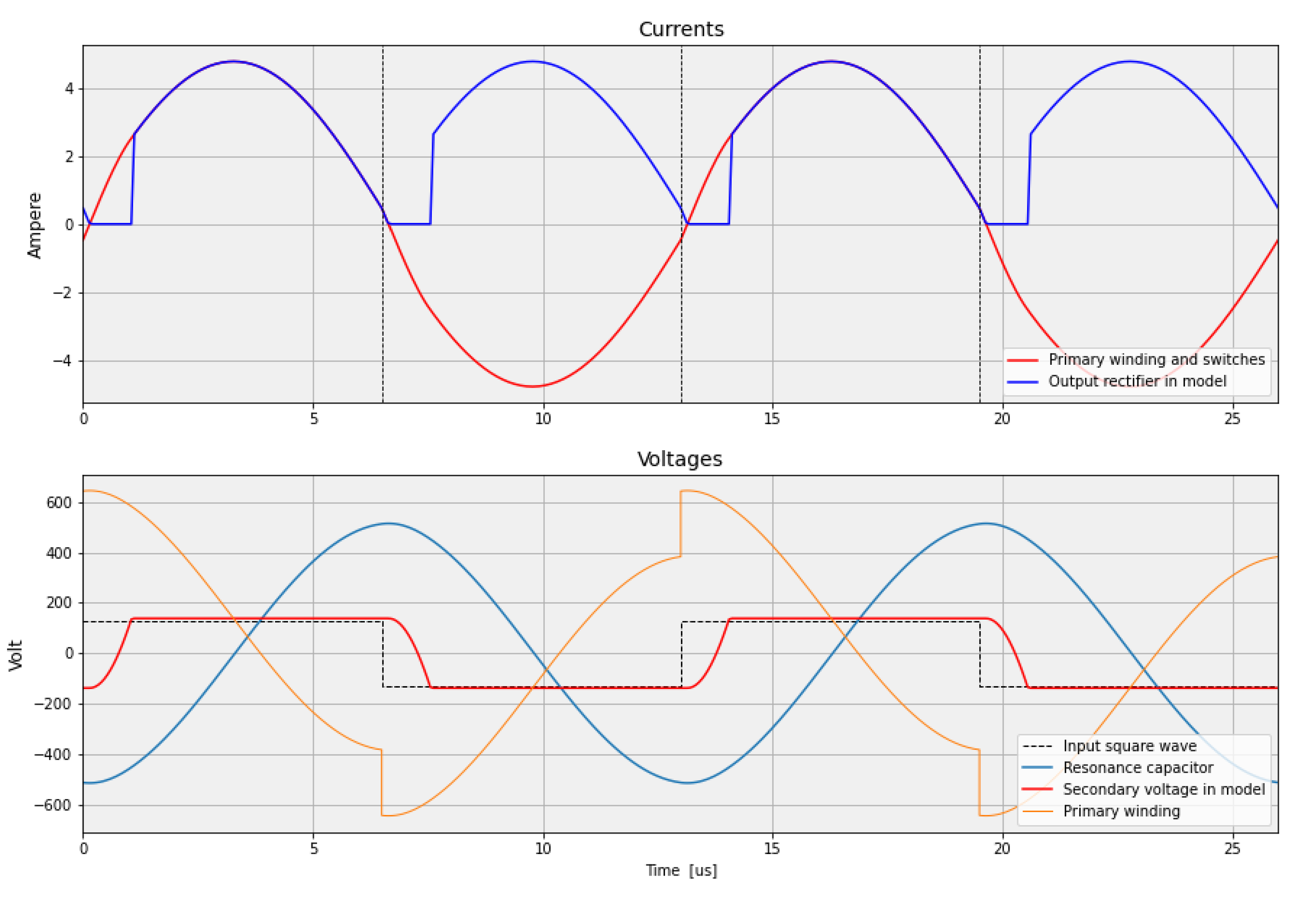

Waveform data:

Frequency	76.9 kHz
Primary current	3.46 A rms
Primary current	9.55 A pp
Secondary current	19.62 A rms
Out-capacitor current	9.66 A rms
Capacitor AC voltage	1028 V pp
Mode	2

Iteration counters
i = 0 in mode 1
j = 152 in mode 2

Transformer data input

```
Afe     = 173e-6     # [m^2]   Core cross section
volfe   = 17.8       # [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  = 180        #         Parallel wires in primary litz
parsec  = 840        #         Parallel wires in secondary litz
temp    = 100        # [deg.C] Winding temperature

Np      = 40         #         Primary turns number (must give leakage inductance = L as defined above)
plotmax = 3.5        # [W]     Max power in power plots. Auto-scale is confusing
```

ETD44. Bobbin = standard. Space between P and S = 10mm. Limited winding height => creepage to core > 2 x 3mm.

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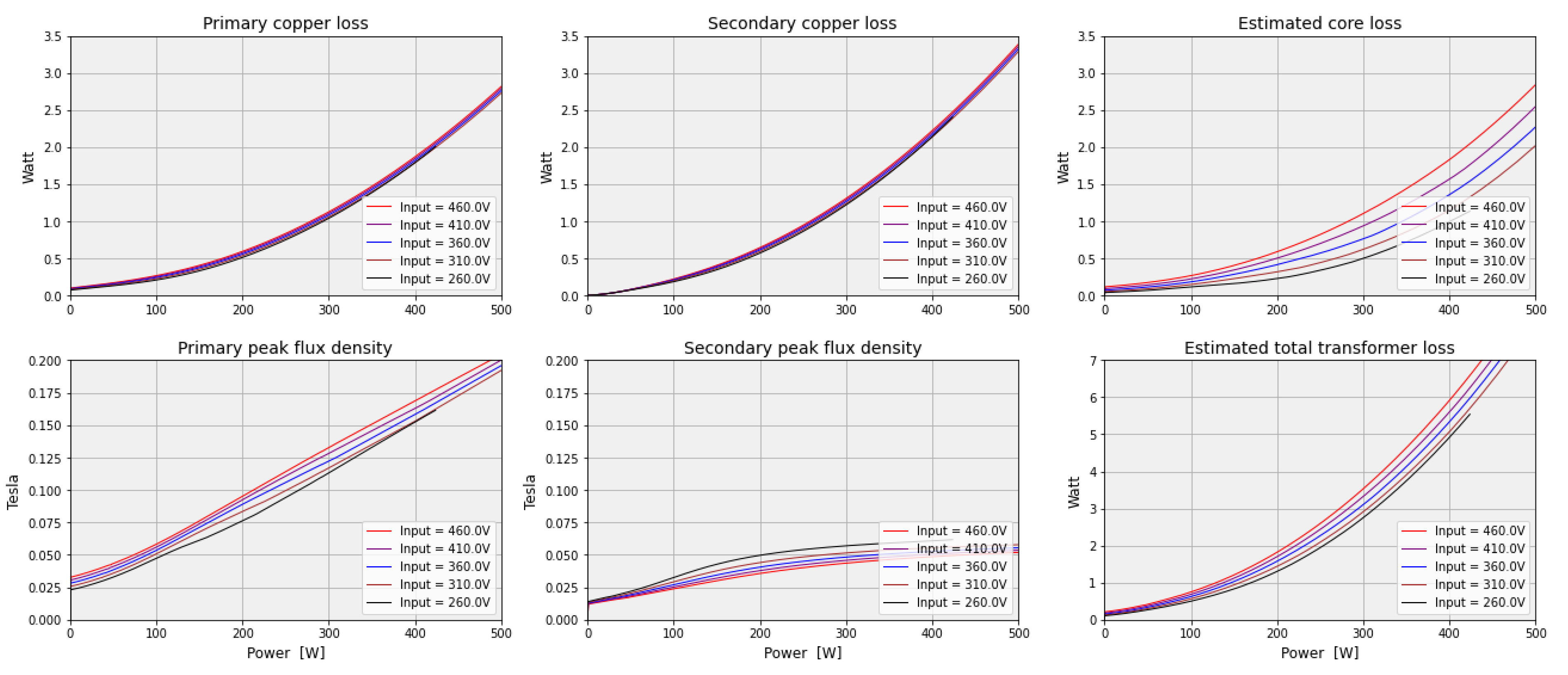
Transformer primary turns	40.0	Primary copper resistance	0.16 Ω
Transformer secondary turns	7.0	Secondary copper resistance	0.006 Ω



External inductor data input

```
AfeL    = 120e-6   # [m^2]   Ferrite cross section area
volL    = 6.53     # [cm^3]  Ferrite volume
feL     = 2        #         Ferrite type: 1: 3C90  2: 3C95   3: 3F3 from ferroxcube
templ   = 100      # [deg.C] Winding temperature
ØL      = 14       # [mm]    Winding average diameter
ØLwire  = 0.1      # [mm]    Wire diameter
parL    = 120      #         Parallel wires in inductor winding

NL      = 45       #         Turns number
plotmax = 1      # [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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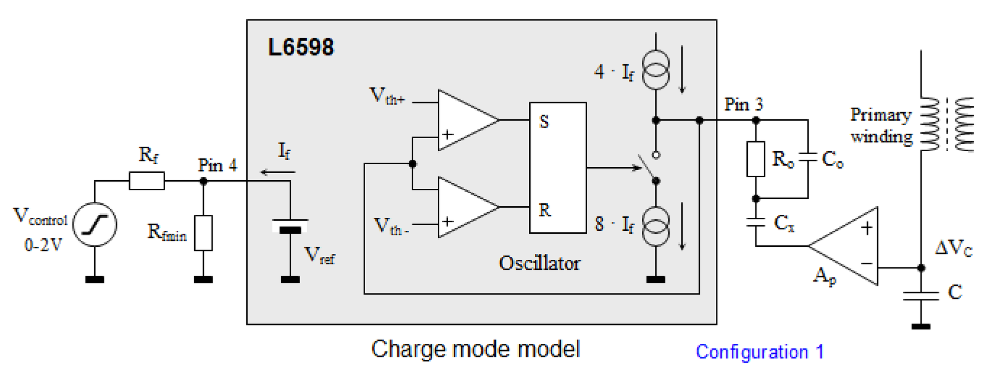
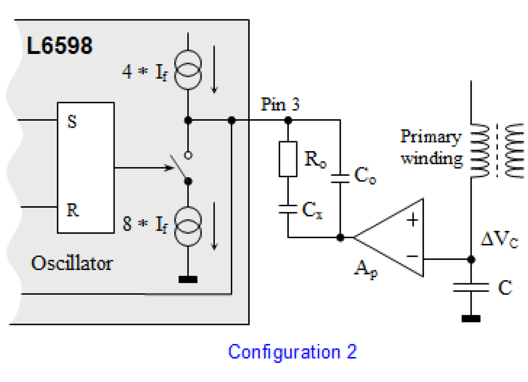
Charge mode application with L6598

Design of control graphs for regulation loop linearity



Charge mode model

Configuration 1



Configuration 2

```
confi = 2          #        RC configuration - see above
Co    = 100e-12    # [F]    Oscillator capacitor
Ro    = 4.7e3      # [ohm]  Resistor in RC network
Cx    = 1e-9       # [F]    DC blocking capacitor
Rfmin = 220e3      # [ohm]  Start-up resistor
Rf    = 25e3       # [ohm]  Frequency programming resistor
Ap    = 0.0021     #        Charge signal inverter gain
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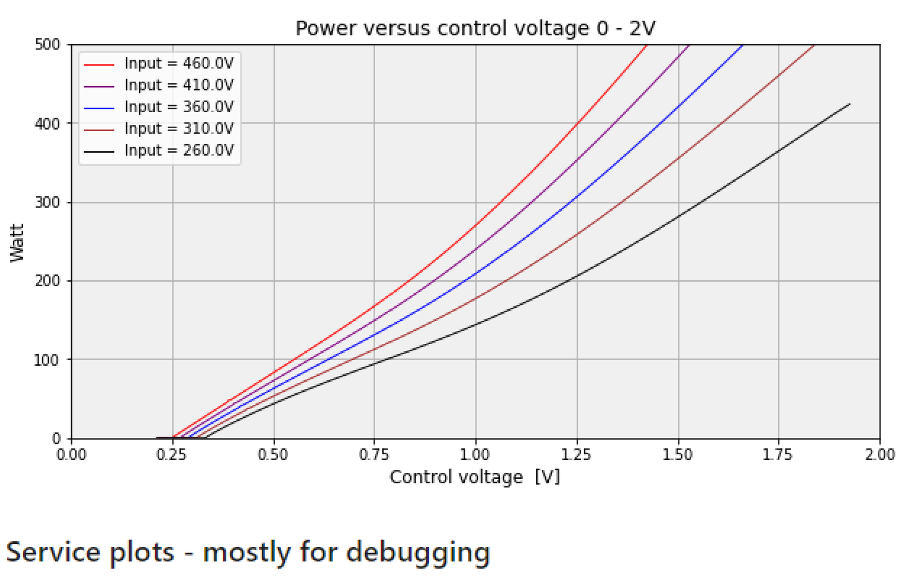

Service plots - mostly for debugging

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User guide

The LCC converter can be preferred over the LLC in cases where input or output voltage cover a large range. For high output voltage the LLC does not work at all - LCC works because Cs can represent part of the inevitable parasitic capacitance in the output winding and rectifier.

This worksheet is an analysis tool intended to let you see how a given set of component data in an LCC converter will work in steady state. By manupulating component data, an LCC can be optimized, but it still requires some engineering skills to know where to look for the optimum.
"First Harmonic Approximation" is often used for the LLC but its usability is doubtful for the LCC. This LCC worksheet is based on accurate voltage and current waveforms in time. It can handle LCC 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 LCC topology.

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

1. Basic LCC 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 LCC 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 L, C, Cs, and Vo

The half- or full bridge is analyzed in an equivalent model with no transformer, see diagrams in first picture. Here Vo is a fictitious output voltage which can be selected arbitrarily. If selected too high, it is difficult to transfer power. If selected too low, rms currents become too high. A good starting point is to set $Vo = Vlow/2$ where Vlow is the lowest desired input voltage with full load.
The ratio between the fictitious Vo and the real Vout determines the turns ratio in the transformer.
The magnetizing inductance should be as high as possible and much larger than L. There should be no air gap in the LCC transformer. The "leakage inductance" L 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.
The LCC can handle large variations in input voltage, however the reactive power which always flows in L and C's becomes inversely proportional to min. input voltage. Wide DC operating ranges have huge consequences for rms losses.

The choice of L and C's is somewhat arbitrary.
Cs mainly affects the no-load frequency. Once you have selected L, choose Cs in the model so that no load is at a desired frequency, for instance close to 300 kHz.
If you reduce L later, you must increase Cs. This increases reactive currents and rms losses, especially at no load. Keep an eye on the plots "Frequency" and "Primary rms currents".
The value of C affects the primary resonance frequency. A lower C reduces the frequency span by increasing the lowest frequency at high load. On the other hand, a lower C will suffer a higher peak-peak voltage which can soon reach the kV range. Keep an eye on the plots "Frequency" and "Resonance capacitor peak-peak voltage". For wider input or output voltage range you have to decrease Vo and accept higher rms currents and 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:	$L_{new} = L * \frac{P}{P_{new}}$	$C_{new} = C * \frac{P_{new}}{P}$	$Cs_{new} = Cs * \frac{P_{new}}{P}$	$Vo_{new} = Vo$
Input voltage scaling:	$L_{new} = L * \left(\frac{Vi_{new}}{Vi}\right)^2$	$C_{new} = C * \left(\frac{Vi}{Vi_{new}}\right)^2$	$Cs_{new} = Cs * \left(\frac{Vi}{Vi_{new}}\right)^2$	$Vo_{new} = Vo * \frac{Vi_{new}}{Vi}$
Frequency scaling:	$L_{new} = L * \frac{f}{f_{new}}$	$C_{new} = C * \frac{f}{f_{new}}$	$Cs_{new} = Cs * \frac{f}{f_{new}}$	$Vo_{new} = Vo$

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 approximately $Vi = 2 * Vo$ the transferrable power is in principle infinite. Below $Vi = 2 * Vo$ the LCC still can transfer a limited amount of power. Test it by setting Vmin arbitrarily low.
If currents or capacitor voltage seem to be inconveniently large, it may be advantageous to use power scaling.
Frequency span over load range and input voltages will be reduced by selecting a higher Cs or a lower C at the cost of a higher primary rms currents and capacitor AC voltage respectively.
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.
The plot "Input capacitor rms current" shows the current stress on the DC supply capacitor, provided you use a full bridge or a half bridge with C split in two as in the diagram above.
The plot "Primary peak-peak current" is useful if you want to make a current limiter based on peak current. Note how independent it is of input voltage, unlike for LLC.
The plots "Primary winding+inductor peak-peak voltage" and "Primary winding+inductor average |volt|" provide useful data if you want to generate a primary aux. voltage by means of an aux. winding in the primary part. If you put a "large" inductor in the recifier, you rectify the "average |volt|", thereby you can some times get an aux. voltage which varies less with input and load. Also, you must know the peak-peak voltage to design adequate insulation in the primary winding.
Zero volt switching relies on the plot "Current at switching instant (for zvs)". Where these graphs reach 0A zero volt lossless switching is lost.
On the other hand, if the switching current rises to a high level at high input voltage, be prepared for extra work for noise mitigation.

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 LCC converters.

With the L-value chosen above, now you directly calculate your primary turns number as $Np = \sqrt{\frac{L_{leak}}{A_{Lleak}}}$. Is secondary turns number Ns a integer number? Probably not. Select another Np until you hit Ns = integer. Adjust Vo slightly if necessary. Go back to the top and adjust leakage inductance to $Ls = A_{Lleak} * Np^2$.
Now fill in the transformer data for your intended transformer type. Choose wire dimensions to fill out your winding space best possible, respecting creepage distances.
Observe the power loss and magentization plots. Does power loss look reasonably small and well distributed between windings and core? Wire loss will probably be dominating. If it turns out that your wire losses get excessive, you can try to reduce Np to get the next lower Ns, and re-adjust L accordingly, if possible use higher wire cross sections. But you then have to increase Cs and rms currents, so your options are limited.
Ultimately, you may have to choose a larger transformer.

In a two-slot transformer you will probably want more spacing between P and S than just a thin wall to get sufficient leakage inductance. A magnetic shunt in this empty space can help you to optimize losses even further.
Be prepared for an iterative process with many steps on your computer before you build your first real transformer.