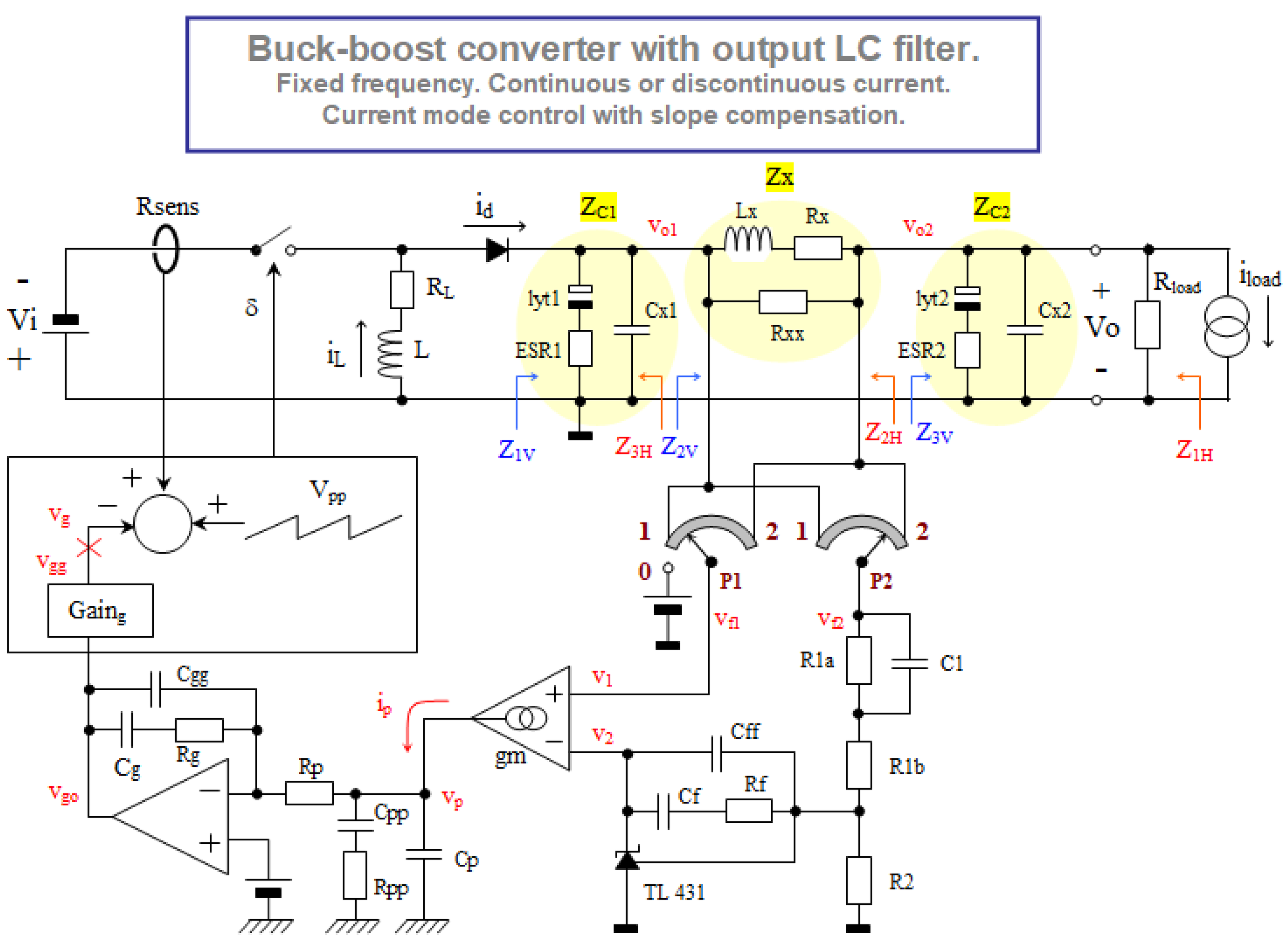
Feedback loop analysis in a buck-boost converter

Open loop gain + phase and closed loop output impedance



Insert your network variables here:

```
'Buck-boost inductor';         L     = 300e-6     ;     RL   = 0
'1st ouput capacitor';         lyt1  = 220e-6     ;     ESR1 = 0.05      ;     Cx1  = 0
'Filter inductor';             Lx    = 5e-6       ;     Rx   = 0         ;     Rxx  = 44
'2nd output capacitor';        lyt2  = 220e-6     ;     ESR2 = 0.05      ;     Cx2  = 0
'Dynamic load resistor';       Rload = 10000

'Error amp gain * bandwidth';    f0dB  = 2e6
'Error amp feedback network';    Rf    = 220e3      ;     Cf   = 2.2e-9    ;     Cff  = 100e-12
'Voltage divider upper part';    R1a   = 100e3      ;     R1b  = 0         ;     C1   = 0
'Voltage divider output';        Vref  = 2.5
'Transcondutance gain[A/V]';     gm    = 1e-3

'gm amplifier load';           Rp    = 0          ;     Cp   = 0
' ';                           Rpp   = 0          ;     Cpp  = 0

'Primary amplifier feedback';    Rg    = 1/gm       ;     Cg   = 1         ;     Cgg  = 0

'Current sense + slope';       Rsens = 0.1        ;     Vpp  = 0.05      # Not both zero!
'Modulator gain';              Gaing = 0.61

'Feedback connection points';    P1    = 0          ;     P2   = 1         # P1 = 1-2 or 0     P2 = 1-2

'Input & output voltage, power'; Vi    = 50         ;     Vo   = 60        ;    P = 40

'Switching frequency';         F     = 100e3
'Start and stop frequency';      fmin  = 10         ;     fmax = 1*F
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Now calculate the response to a step load at frequency Fo and step size Istep.

```
'Test step frequency [Hz]';      Fo     = 500
'Load current step [A]';         Istep  = 1
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Continuous Current Mode
Right half plane zero:                 18.1 kHz
Relative slope (slope/downslope):       0.25
Required relative slope for stability:  0.08
F/2 progression factor   pro:          -0.69
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Lower resistor in voltage divider R2 =  4.35e+03 ohm
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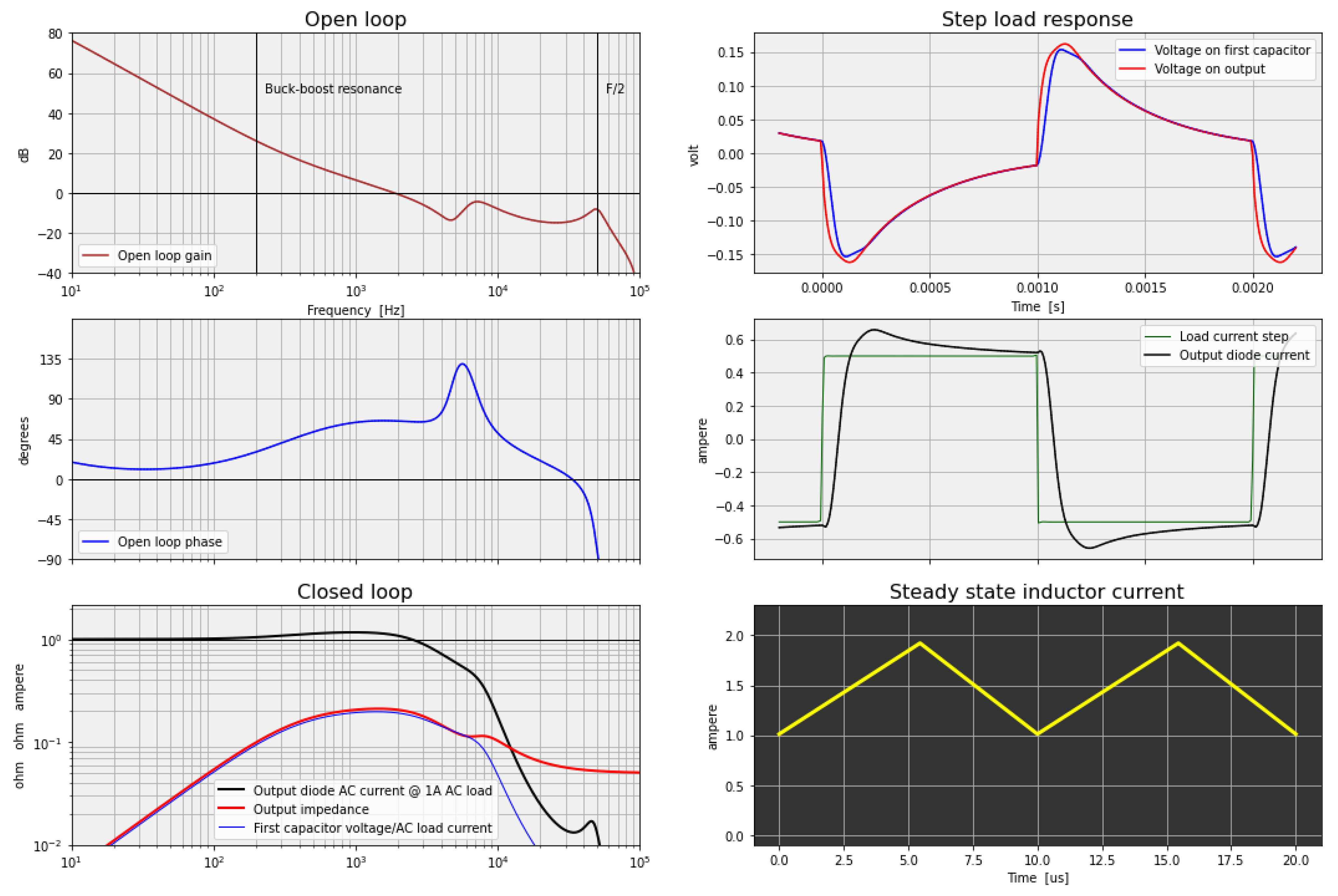

Sub-circuit gain and phase:

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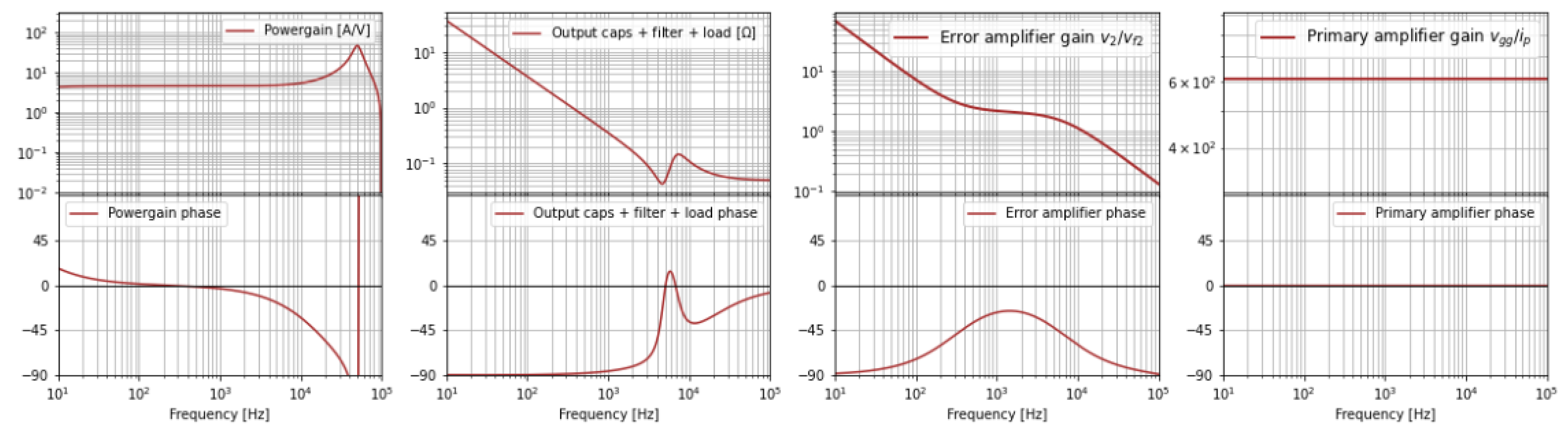

Nyquist plot of open loop:

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MAX = 3                    # x and y axis limits in Nyquist plot (positive, integer!)
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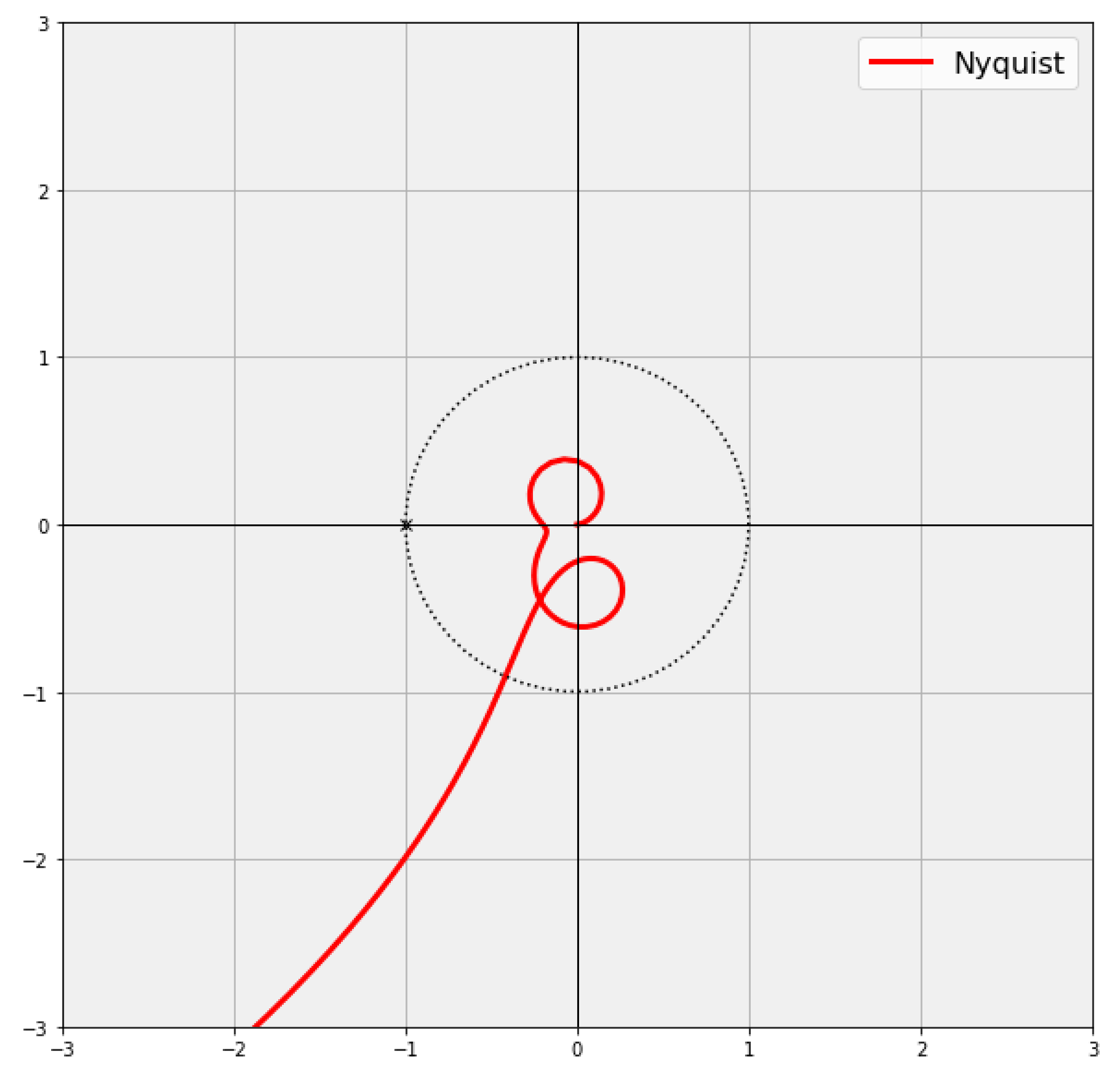

User guide.

This worksheet calculates open loop (small signal) gain + phase and closed loop properties of a buck-boost converter. It also shows you the response to a step load at a selected frequency and amplitude. The converter can be in continuous current or discontinuous current mode. The control scheme can be voltage mode (duty cycle control) or current mode control with any slope compensation.

Units are [Volt], [Ampere], [Watt], [ohm], [Henry], [Farad], [seconds], [Hz].

To enable you to clearly see the consequence of a change in input, the worksheet adds graphs of some of the previous outputs in dotted lines. If you want to see plots without previous outputs, run the worksheet again with no input change.

Once you have made your choices of input data, the worksheet will print what mode you are in and for current mode control it will indicate if you have enough slope compensation for subharmonic stability. Voltage mode control is when you set Rsens = 0. Pure current mode control is when you set Vpp = 0. In continuous current mode (CCM) you need slope compensation above 50% duty cycle. Insert Vpp > 0 to add slope compensation. The more slope compensation you use, the more you will approach the properties of voltage mode control.
This worksheet also includes a model of the "sampled" sub-harmonic ringing or instability at F/2 in current mode control. You can de-select this model by setting sub = "no" in the beginning of the first code cell which gives you the possibility to study the additional effect and extra accuracy of the sub-harmonic modelling in CCM.

The sub-harmonic progression factor pro:

pro < -1 means unconditional sub-harmonic oscillation.
-1 < pro < -0.5 is inherently stable but can become unstable at F/2 when the outer feedback loop is closed.
pro = 0 occurs if slope = downslope, which means that a current error settles within one switching cycle.
With pure voltage mode control (Rsens = 0), pro = 1.

Nyquist plot:

A Nyquist plot is shown in the end of the worksheet. According to Nyquist, if the point (-1,0) is encircled by the graph, the converter is self oscillating. However, sub-harmonic oscillation does not always obey that rule.
You may have to increase MAX to see the encirclement.

The loop behaviour may depend strongly on the steady state operating condition of your buck-boost converter. You should do the calculation at low and high power and at low and high input voltage and assure that your design is stable in all working conditions.

If you use electrolytic capacitors in the output you should also test your design with low ESR and high ESR (in cold capacitors the ESR may increase tenfold). Low ESR can give loop problems at medium frequencies, high ESR can give you problems at high frequencies.

There is a high ripple current on the output of a buck-boost converter, so we often need the option to use an LC ripple suppression filter. This filter may have dramatic influence on the loop performance. The worksheet includes several possibilities of connecting the feedback network to this filter, defined by the potentiometer settings P1 and P2. Stability is often best, if P1 = 1. DC regulation is perfect, when P2 = 2. Usually this is the best choice. If the first feedback point is fed from an independent voltage source set P1 = 0.

In cases where output capacitors are not very large, the output filter can create resonance at critical frequencies. If you adjust P1 and/or P2 between 1 and 2 you can sometimes cancel this resonance in the feedback loop so that the loop does not know about it. But the resonance will still be present in the closed loop output impedance. Often you can minimize filter ringings by adjusting P1 and P2 slightly lower than this cancellation point. But be careful - this design technique is very sensitive to tolerances.
It is a good idea to start the loop analysis without an inductor in the LC filter, and then, when the loop looks nice, you insert the filter and play with the feedback connection points. You may also have to damp the filter with Rxx.

In the loop model the popular TL431 (LM431 etc. .) has been used. You can also use a separate reference and an inverting op-amp instead. Or you can use a non-inverting op-amp, but in that case you need new equations for the error amplifier.

If you use duty cycle (voltage mode) control in discontinuous current mode, the loop calculator is not accurate due to the dead time ringing in the inductor + parasitic capacitances. Loop gain can be very dependent on whether the switch turns on in a ringing valley or on a ringing top. Current mode control is in principle insensitive to the dead time ringing.

Always verify the calculations by experiments. You can perform an open loop gain/phase analysis if you have an analyzer for that, or you can check the size and shape of the step load response.