LLC Resonant Converter

Wednesday, August 30, 2023 10:43 AM

Parameters:

$V_{in} = 105\,V_{DC} - 135\,V_{DC} \approx 120\,V_{DC}$ $P = 600W$ $V_{out} = 12\,V_{DC}$ $I_{out} = 50A$

$V_{rpp} \leq 120mV$ Efficiency $\geq 90\%$ $f_{sw} = 70kHz - 150kHz$ (100kHz) line & load regulation $\leq 1\%$

Turns ratio -

$$n = M_g \times \frac{V_{in}}{2V_o} = \left.\frac{V_{in\text{-}nom}}{2V_{o\text{-}nom}}\right|_{M_g=1} = \frac{120V}{2(12V)} = 5 \qquad \boxed{n=5}$$

M_{g_min} & M_{g_max} -

$$M_{g\_min} = \frac{n \times (V_{o\_min} + V_F)}{(V_{in\_max})/2}$$

$n = 5$ $V_{o\_min} = 12 \times 0.99 = 11.88V$

V_F = forward drop of secondary side diode $= 1.1V$

$V_{in\_max} = 135V$

$$= \frac{5 \times (11.88V + 1.1V)}{67.5V}$$

$$\boxed{M_{g\_min} = 0.956}$$

$n = 5$ $V_{o\_max} = 12 \times 1.01 = 12.12V$

$V_F = 1.1V$ $V_{in\_min} = 105V$

$$V_{loss} = \frac{\left(\frac{600W}{92\%} \times 8\%\right)}{50A} = 1.04V$$

$$M_{g\_max} = \frac{n \times (V_{o\_max} + V_F + V_{loss})}{(V_{in\_min})/2}$$

$$= \frac{5(12.12V + 1.1V + 1.04V)}{52.5V}$$

$$M_{g\_max} = 1.358 \times 110\% = 1.494 \qquad \boxed{M_{g\_max} = 1.494}$$

Choose L_n & Q_e -

$L_n = 5$ $Q_e = 0.5$

Check M_g & F_n on graph -

$$f_n = \frac{f_{sw}}{f_o} \rightarrow f_{sw} = f_o = 100kHz \rightarrow f_n = 1$$

Create curves for diff Q_e at fixed L_n

$$M_g = \left| \frac{L_n \times f_n^2}{[(L_n+1) \times f_n^2 - 1] + j[(f_n^2 - 1) \times f_n \times Q_e \times L_n]} \right| \text{ at } L_n = 5 \begin{cases} 0 \leq M_g \leq 2 \text{ (y-axis)} \\ 0.1 \leq f_n \leq 10 \text{ (x-axis)} \\ Q_e = 0.1, 0.2, 0.5, 0.8, 1, 2, 5, 8, 10 \end{cases}$$

(imaginary part reps. ϕ)

$\boxed{L_n = 5 \quad Q_e = 0.275}$

operating region

$M_{g\_max} = 1.494 \quad M_{g\_min} = 0.956$

$f_{n\_max} = 1.13 \quad f_{n\_min} = 0.57$

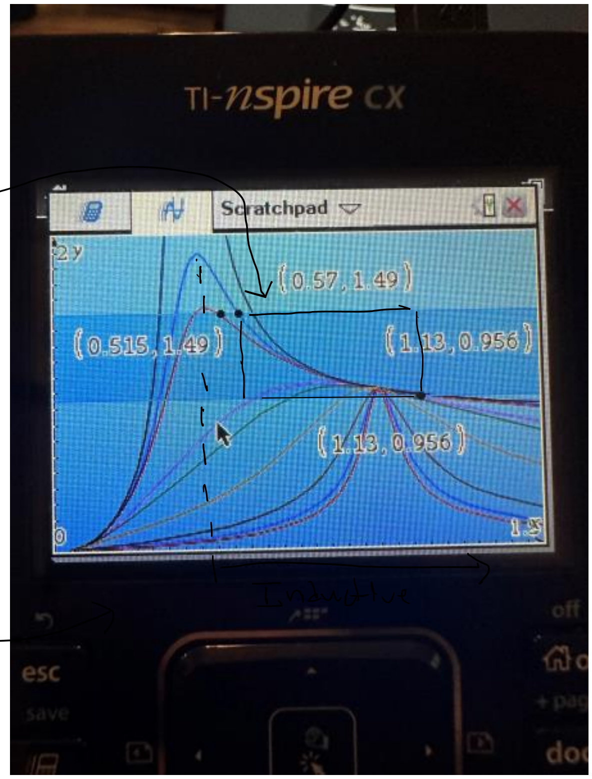
Blue line → $Q_e = 0.275$

Red line → $Q_e = 0.35$

(Probably max usable Q_e)

Should only operate in inductive region

($f_{sw} \geq$ f @ max peak of curve)



R_e calculation -

$n = 5 \quad V_o = 12V \quad I_{o,100\%} = 50A \quad I_{o,110\%} = 55A$

$$R_e = \frac{8 \times n^2}{\pi^2} \times \frac{V_o}{I_o}$$

$$R_e \text{ @ } 100\% \text{ load} = \frac{8 \times (5)^2}{\pi^2} \times \frac{12}{50} = \boxed{4.86\ \Omega}$$

$$R_e \text{ @ } 110\% \text{ load} = \frac{8 \times 5^2}{\pi^2} \times \frac{12}{55} = \boxed{4.42\ \Omega}$$

Resonant Parameters -

$$C_r = \frac{1}{2\pi \times Q_e \times f_o \times R_e}$$

$Q_e = 0.275 \quad f_o = 100kHz$

$R_e = 4.86\ \Omega$

$$C_r = \frac{1}{2\pi(0.275)(100k)(4.86)} = \boxed{1.191\ \mu F}$$

$$L_r = \frac{1}{(2\pi \times f_o)^2 \times C_r} = \frac{1}{(2\pi(100k))^2 \cdot (1.191\mu)} = \boxed{2.127\ \mu H}$$

$$L_r = \frac{1}{(2\pi \times f_0)^2 \times C_r} = \frac{1}{(2\pi(100k))^2 \cdot (1.191\mu)} = \boxed{2.127\ \mu H}$$

$$L_m = L_n \times L_r \qquad L_n = 5 \qquad L_m = 5(2.127\mu) = \boxed{10.635\ \mu H}$$

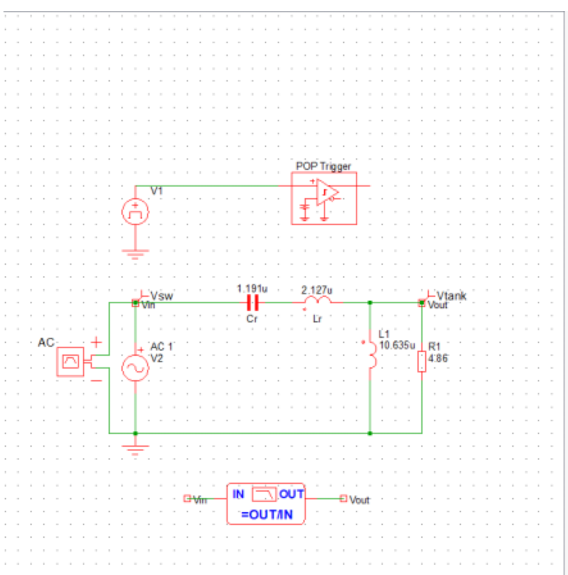
<u>Verify circuit</u> -

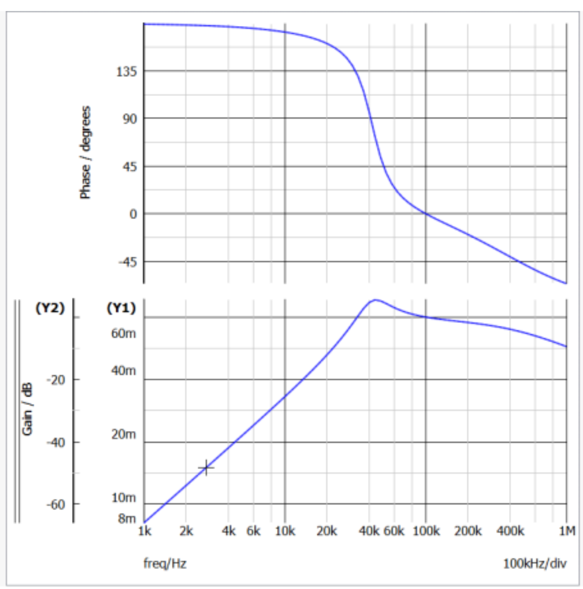
$$f_0 = \frac{1}{2\pi\sqrt{L_r \times C_r}} = \frac{1}{2\pi\sqrt{2.127\mu \times 1.191\mu}} = \boxed{99.996\ kHz}\ \checkmark$$

$$L_n = \frac{L_m}{L_r} = \frac{10.635\mu}{2.127\mu} = \boxed{5}\ \checkmark$$

Q_e @ 100%
$$= \frac{\sqrt{L_r / C_r}}{R_e} = \frac{\sqrt{(2.127\mu H)/(1.191\mu F)}}{4.86} = \boxed{0.275}\ \checkmark$$

Q_e @ 110%
$$= \frac{\sqrt{(2.127\mu H)/(1.191\mu F)}}{4.42} = \boxed{0.302}\ \checkmark$$





$Q_e = 0.275$ - 100% load

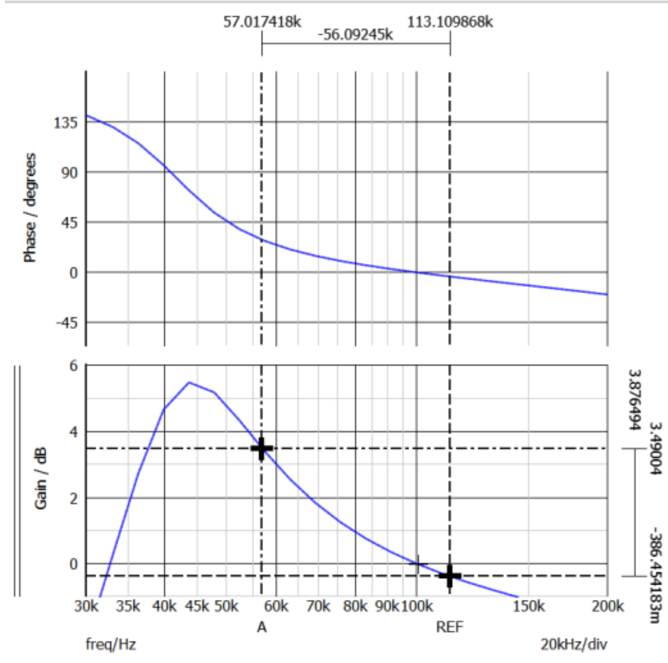
$R_e = 4.86\,\Omega$

$M_{g\_max} = 3.487$ dB

$M_{g\_min} = -0.341$ dB

$f_{n\_max} = 112.995\text{kHz} \approx 113\text{KHz}$

$f_{n\_min} = 56.948\text{kHz} \approx 57\text{KHz}$



$Q_e = 0.302$ 110% load

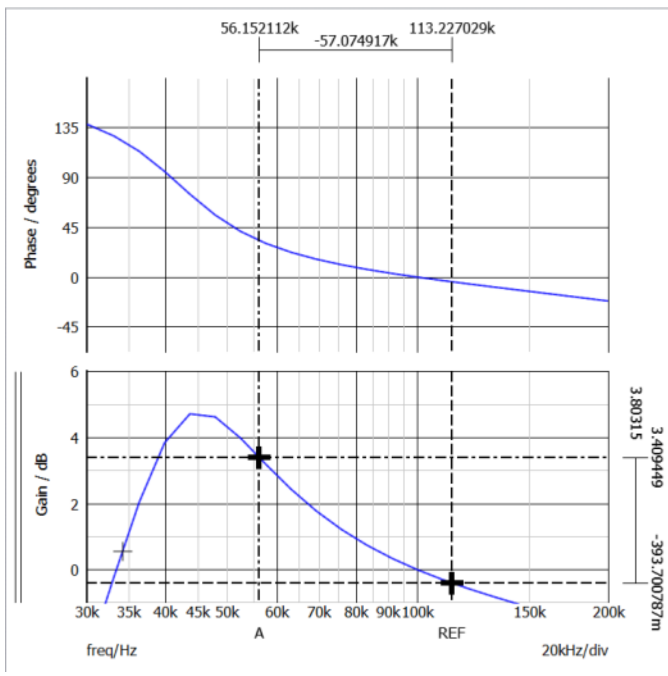
$R_e = 4.42\,\Omega$

$M_{g\_max} = 3.487$ dB

$M_{g\_min} = -0.341$ dB

$f_{n\_max} = 112.995\text{kHz} \approx 113\text{KHz}$

$f_{n\_min} = 56.152\text{kHz} \approx 56\text{KHz}$



Primary & Secondary side currents -

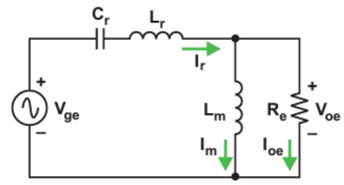
$$I_{oe} = \frac{\pi}{2\sqrt{2}} \times \frac{I_o}{n} \qquad I_o = 50\,A \qquad n = 5$$

110% overload $\rightarrow$ $I_{oe} = \underline{12.22\,A}$ (Primary load current)

$$I_m = 0.901 \times \frac{nV_o}{\omega L_m} \qquad V_o = 12 \qquad L_m = 10.635\,\mu H$$

$f_{sw\_min} = 56\text{kHz}$

at min. $f_{sw} \rightarrow I_m = 14.45\ A$



$I_r = \sqrt{I_m^2 + I_{oe}^2} = \boxed{18.92 A}$

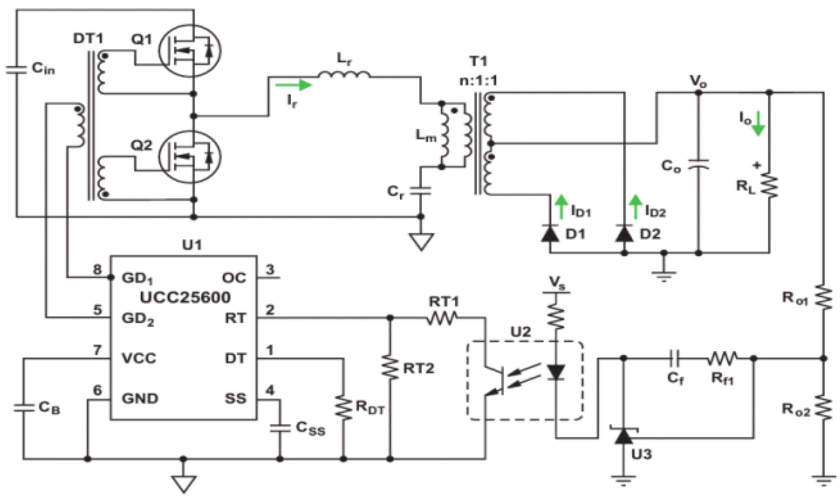


Fig. 15. Proposed circuit for the design example.

$I_{oe\_s} = n \times I_{oe} = 61.1 A$

$I_{sw} = \frac{\sqrt{2} \times I_{oe\_s}}{2} = 43.2 A$

$I_{sav} = \frac{\sqrt{2} \times I_{oe\_s}}{\pi} = 27.5 A$

Capacitor voltage —

$V_{cr} = X_{cr} \times I_r = \frac{I_r}{\omega C_r}$

$I_r = 18.92\ A$

$f = 100k$

$C_r = 1.191\ \mu F$

$V_{cr} = 25.28\ V$

$V_{in\_max} = 135V$

$V_{cr\_rms} = \sqrt{\left(\frac{V_{in\_max}}{2}\right)^2 + V_{cr}^2}$

$V_{cr\_rms} = 72.08\ V$

$$V_{Cr_p} = \frac{V_{in\_max}}{2} + V_{Cr}\sqrt{2}$$ $\boxed{V_{Cr_p} = 103.25\ V}$

MOSFETS -

$V_{in} = 135\ V$ $\boxed{V_{Q_{1p}} = V_{Q_{2p}} = 200\ V}$

$$\boxed{I_{Q_{1\_rms}} = I_{Q_{2\_rms}} = I_r = 18.92\ A}$$

ZVS Design -

$$I_{m\_min} = 0.901 \times \left(\frac{n \times V_o}{2\pi f_{sw} \times L_m}\right)$$

$$I_{m\_min} = 7.16\ A$$

$f_{sw\_max} = 113\ kHz$

$L_m = 10.635\ \mu H$

Deadtime -

$$\frac{1}{2}(L_m + L_r)\, I_{mp}^2 = 654 \times 10^{-6}\ \text{joules}$$

$$\frac{1}{2}(2 C_{eq}) \times V_{in}^2 = 28.8 \times 10^{-9}\ \text{joules}$$

$28.8 \times 10^{-9} \leq 654 \times 10^{-6}$ ✓

$C_{eq} = C_{ds} \approx 200\,pF$ in Mosfets

$t_{dead} \geq 16 \times C_{eq} \times f_{sw} \times L_m$ $t_{dead} \geq 3.5\ ns$

$$\boxed{t_{dead} = 10\,ns}$$

Diodes -

$$V_D = \frac{V_{in\_max}/2}{n} \times 2 = 27\ V$$

$$I_D = \frac{I_{out\_s}\sqrt{2}}{\pi}$$

$I_{out\_s} = 61.1\ A$

$$\boxed{I_D = 27.5\ A \quad V_D = 27\ V}$$

Output Filter —

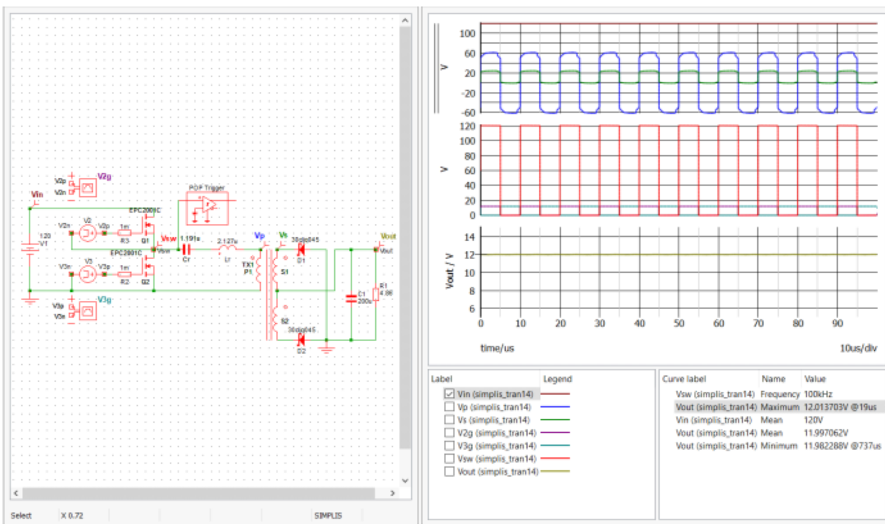
$$I_{C_o} = 0.482 \times I_o \Big|_{I_o = 50A}$$

$$\boxed{I_{C_o} = 24.1A}$$

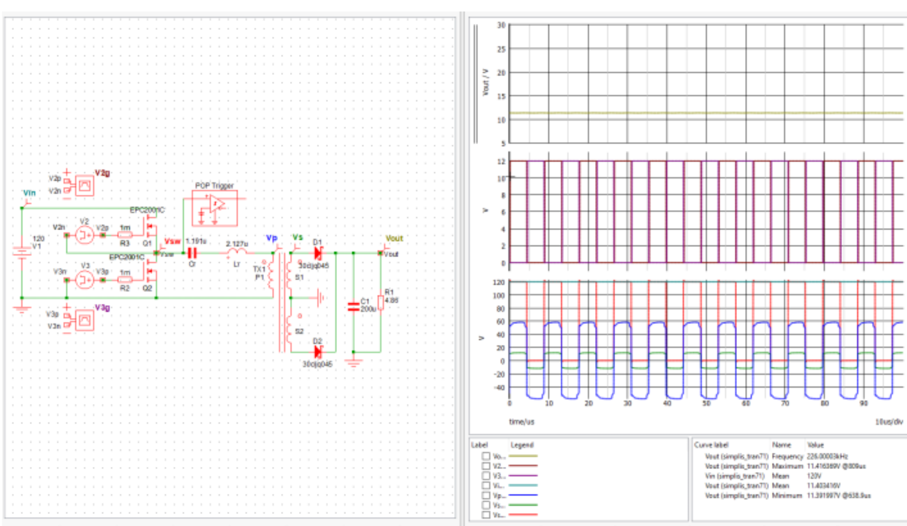
$$ESR_{max} = \frac{V_{o-pp}}{\frac{\pi}{2} \times I_o} \Bigg|_{\substack{V_{o-pp} = 120mV \\ I_o = 50A}}$$

$$\boxed{ESR_{max} = 1.53 m\Omega}$$

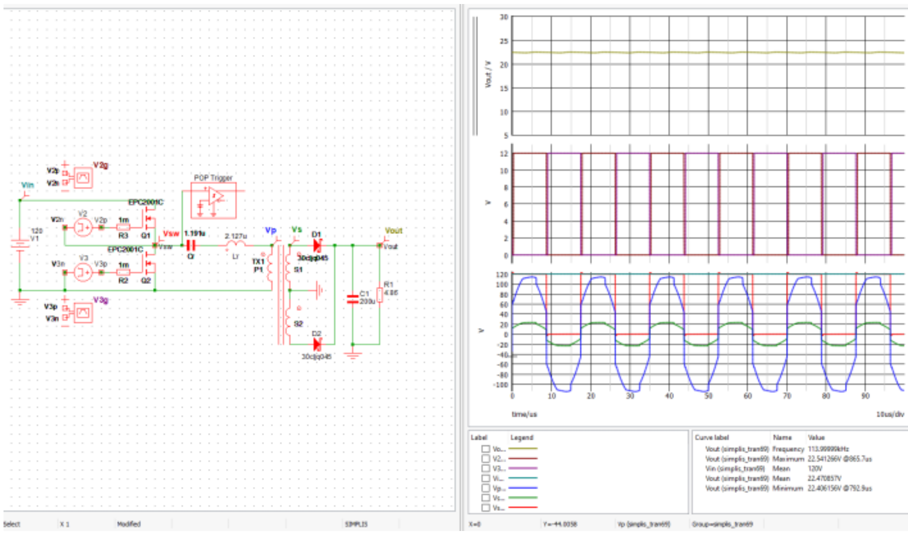
Transient @ $f_{sw} = 100kHz$ $V_o = 12.01V$



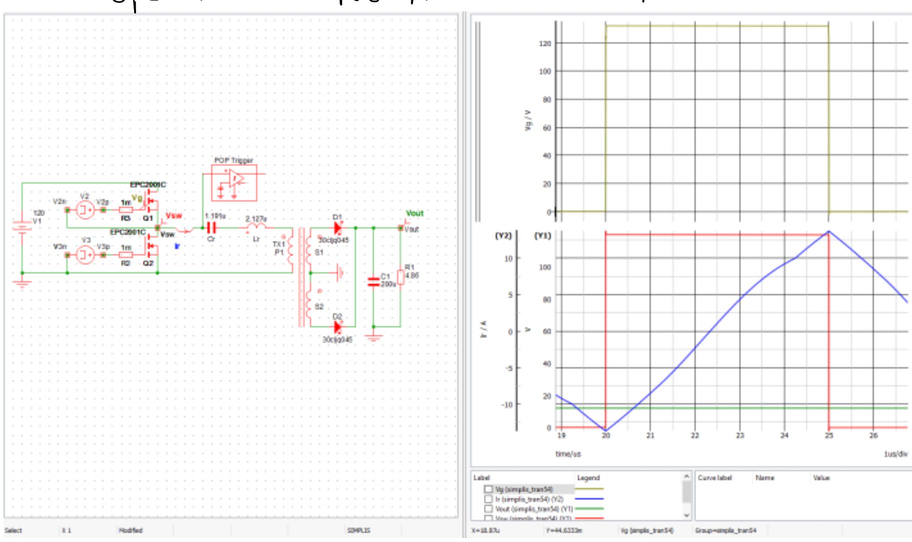
Transient @ $f_{sw} = 113kHz$ $V_o = 11.42V$

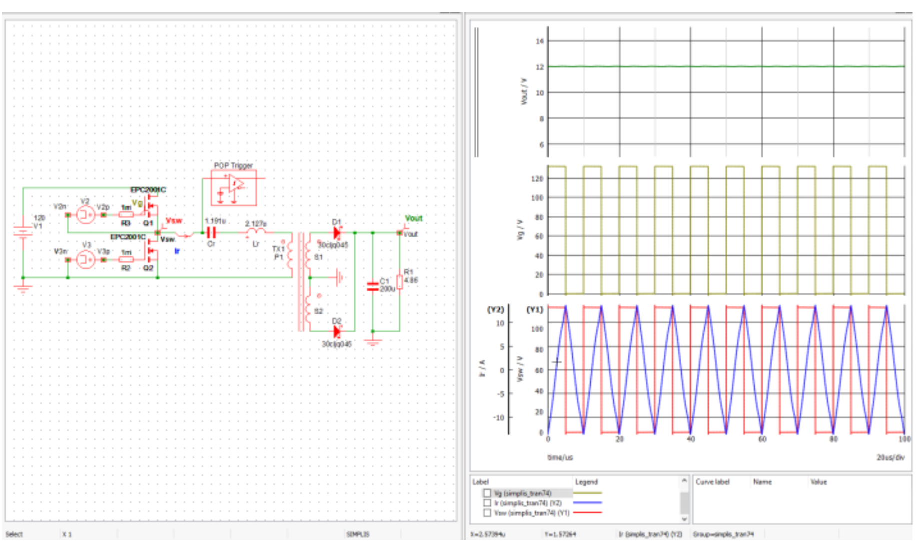


Transient @ $f_{sw} = 56kHz$ $V_o = 22.54V$

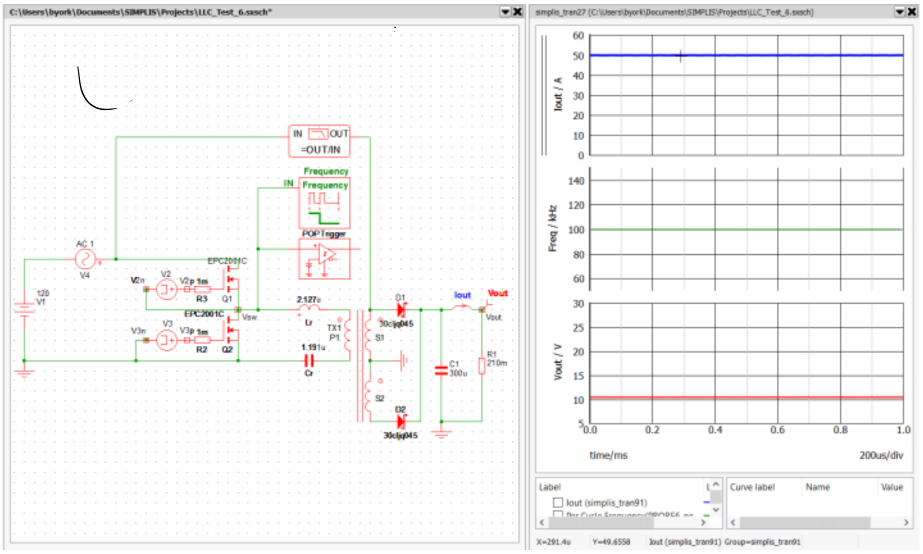


ZVS Operation – No Miller Effect

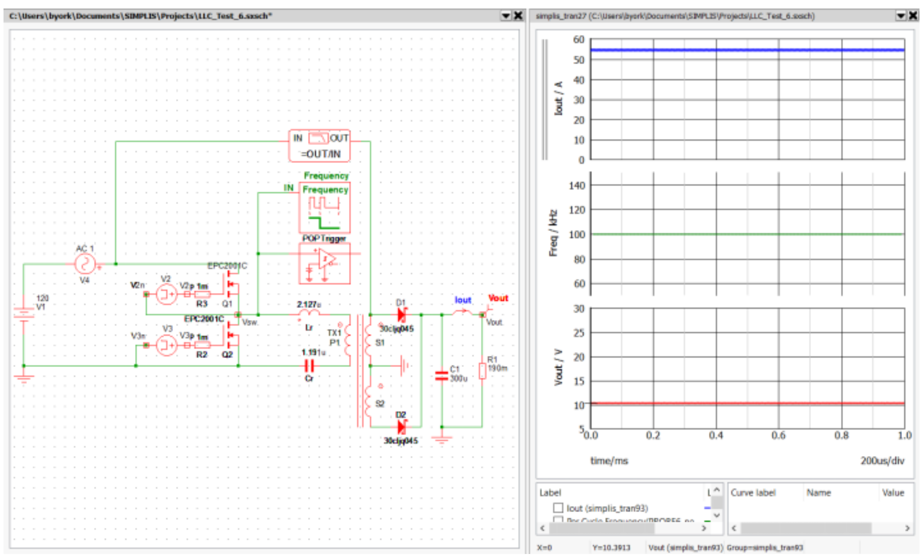




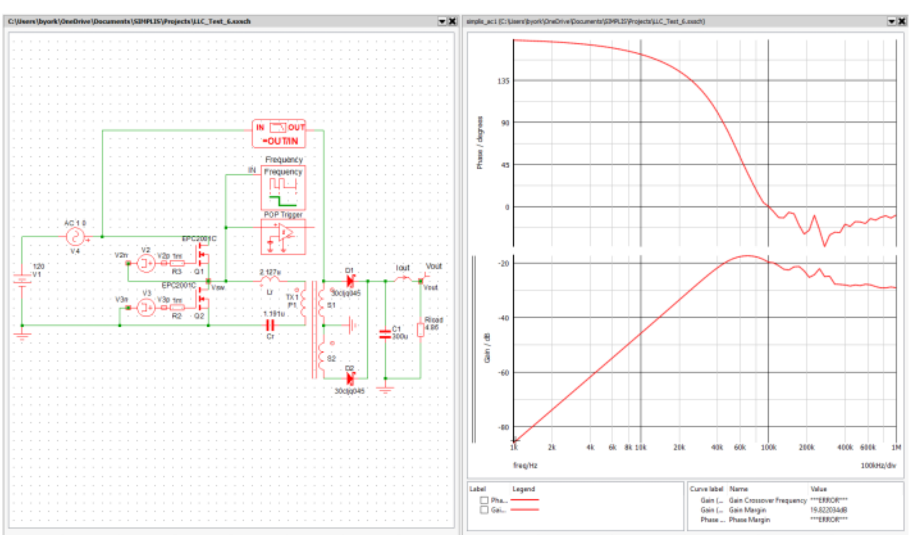
$R_L = 210\ m\Omega$ @ 100% load $[P = 50A \times 10.6V = 530W]$



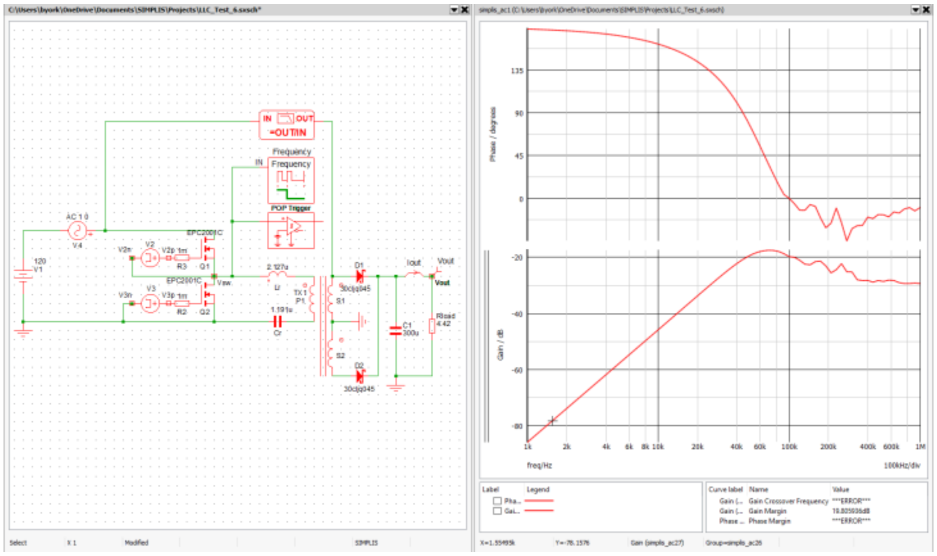
$R_L = 190m\Omega$ @ 110% load $[P = 55A \times 10.3V = 566.5\ W]$



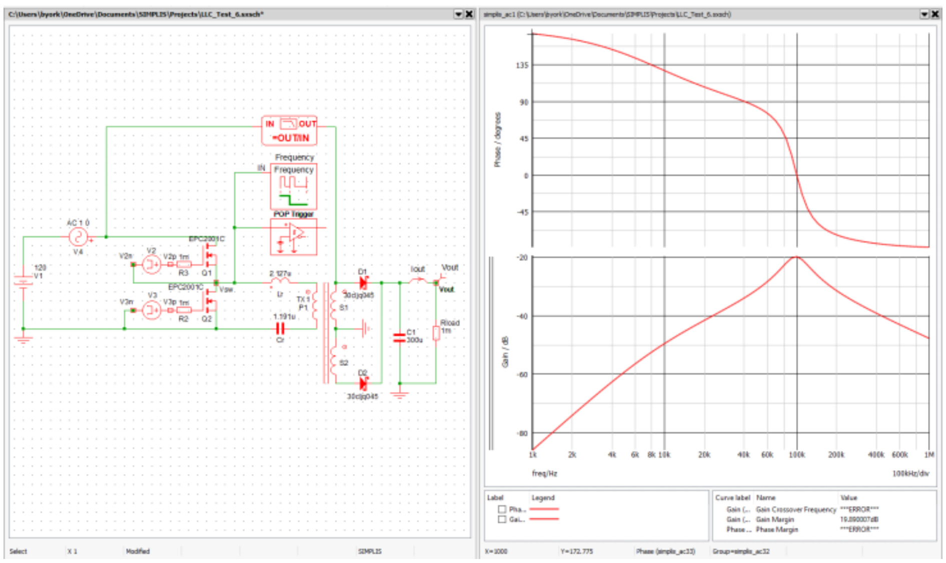
Voltage Gain
100% load (4.86 ohms)



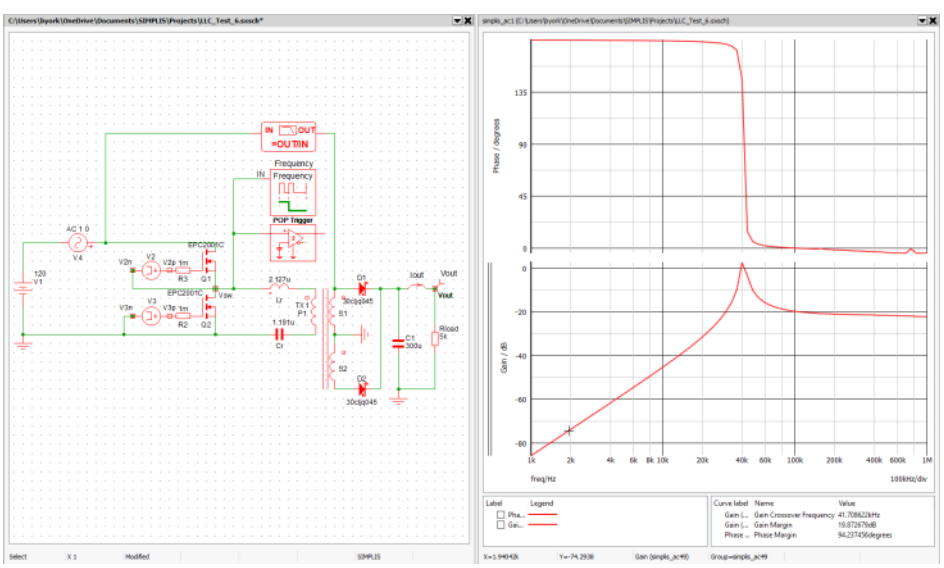
110% load (4.42 ohms)

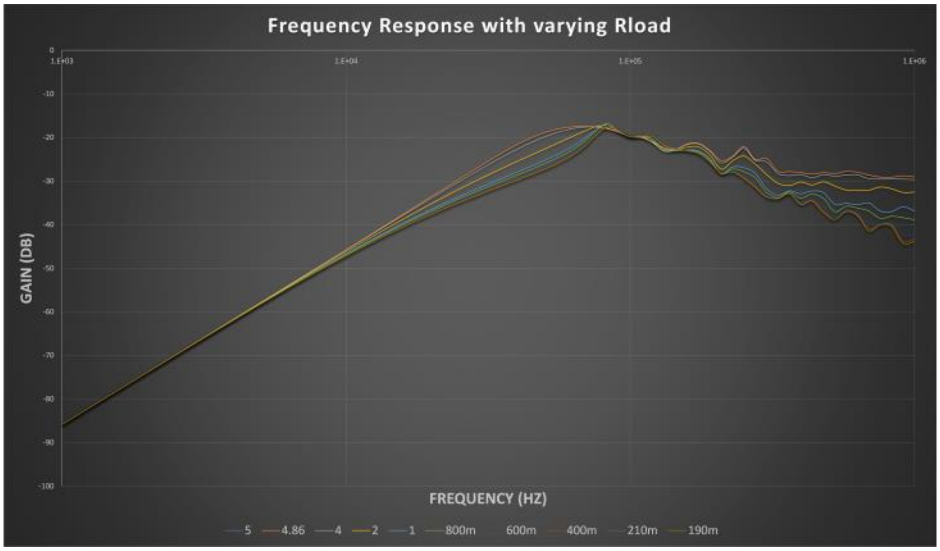


Heavy Load

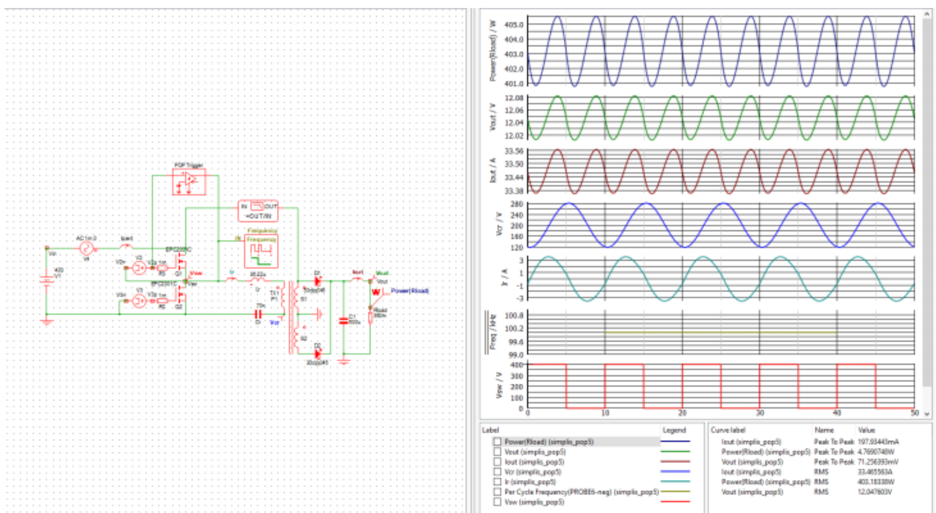


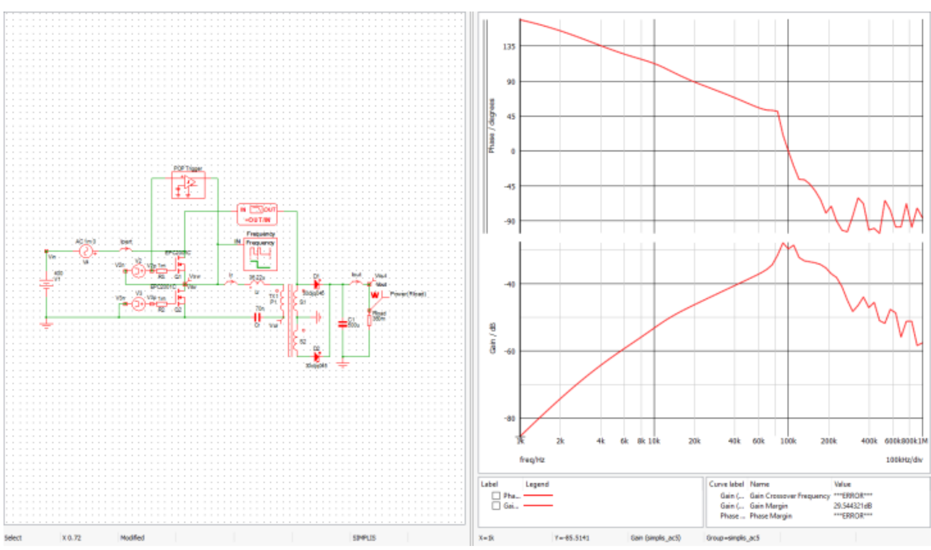
Light load





Fix





Freq domain with time domain partial correction –

$$(I_o)^2 R_L = \frac{1}{2}\left(I_{(1),pk}\right)^2 \frac{R_{eq}}{n^2} \qquad R_{eq} = \frac{n^2 R_L}{2}\,\frac{\left(1-(a/\pi)^2\right)^2}{\cos^2(a/2)}$$

$a = 5\mu s$ $b = 5\mu s$