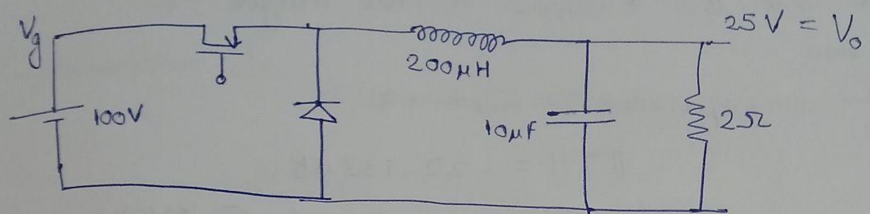
Buck converter design with voltage control and active emi filter

Buck Converter



$f_s \rightarrow$ switching frequency 250 KHz PWM.

$D = 0.25$ (Duty Cycle)

I) Design of closed loop control.

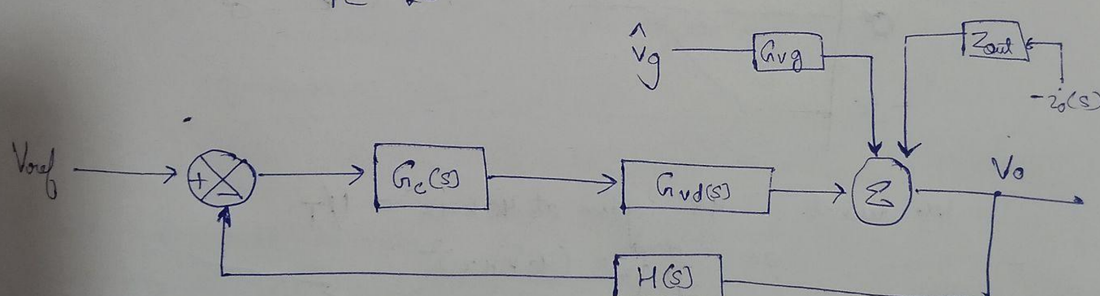
Small signal Model.

$$\hat{v}_o = G_{vd}\,\hat{d} + G_{vg}\,\hat{v}_g - Z_{out}\,\hat{i}_{out}(s)$$

Output Voltage

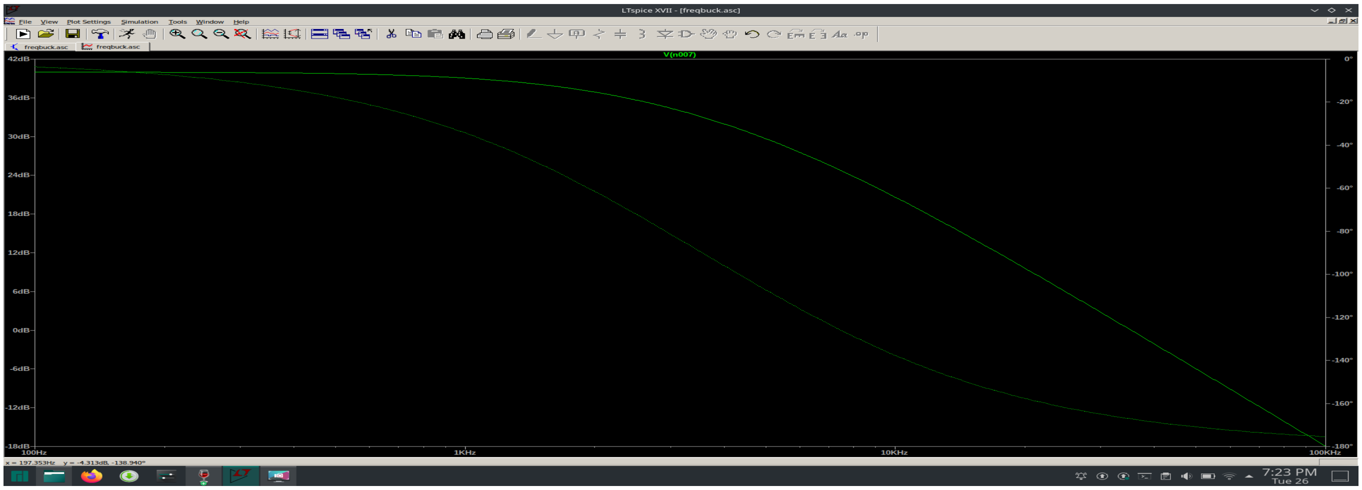
$$G_{vd} = \frac{V_g}{(LC)\left[s^2 + \frac{s}{rC} + \frac{1}{LC}\right]} \qquad Z_{out}(s) = \frac{s}{C\left[s^2 + \frac{s}{rC} + \frac{1}{LC}\right]}$$

$$G_{vg} = \frac{D}{(LC)\left[s^2 + \frac{s}{rC} + \frac{1}{LC}\right]}$$

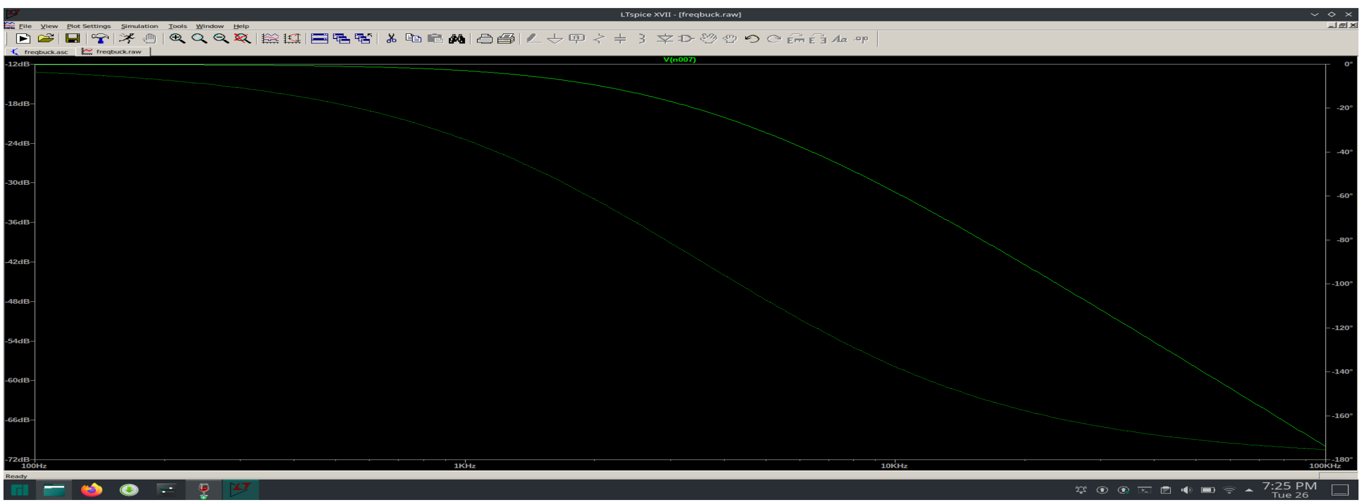


$H(s) \longrightarrow$ Sensor gain

$G_c(s) \longrightarrow$ compensator to be designed.


LTspice XVII - [freqbuck.asc]
File View Plot Settings Simulation Tools Window Help
freqbuck.asc
freqbuck.asc
V(n007)
42dB
36dB
30dB
24dB
18dB
12dB
6dB
0dB
-6dB
-12dB
-18dB
0°
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
100Hz
1KHz
10KHz
100KHz
7:23 PM
Tue 26

Gvd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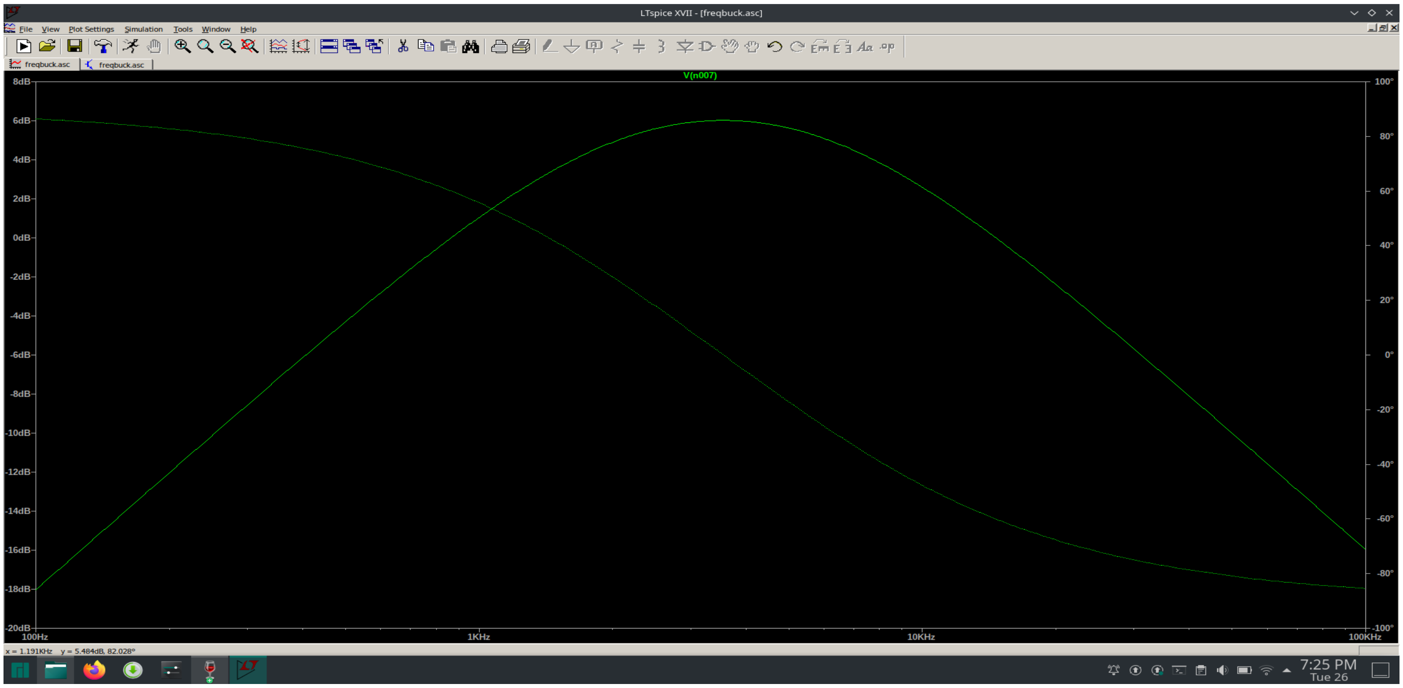
File View Plot Settings Simulation Tools Window Help
freqbuck.asc
freqbuck.raw
V(n007)
-12dB
-18dB
-24dB
-30dB
-36dB
-42dB
-48dB
-54dB
-60dB
-66dB
-72dB
0°
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
100Hz
1KHz
10KHz
100KHz
Ready
7:25 PM
Tue 26

Gvg


LTspice XVII - [freqbuck.asc]
V(n007)
8dB
6dB
4dB
2dB
0dB
-2dB
-4dB
-6dB
-8dB
-10dB
-12dB
-14dB
-16dB
-18dB
-20dB
100°
80°
60°
40°
20°
0°
-20°
-40°
-60°
-80°
-100°
100Hz
1KHz
10KHz
100KHz
x = 1.191KHz y = 5.484dB, 82.028°
7:25 PM
Tue 26

Zout

Lets design $G_c(s)$

say we want $BW \rightarrow 40KHz$ & Phase Margin $\sim 60°$

then

for uncompensated $T = G_{vd}(s) \times H(s)$

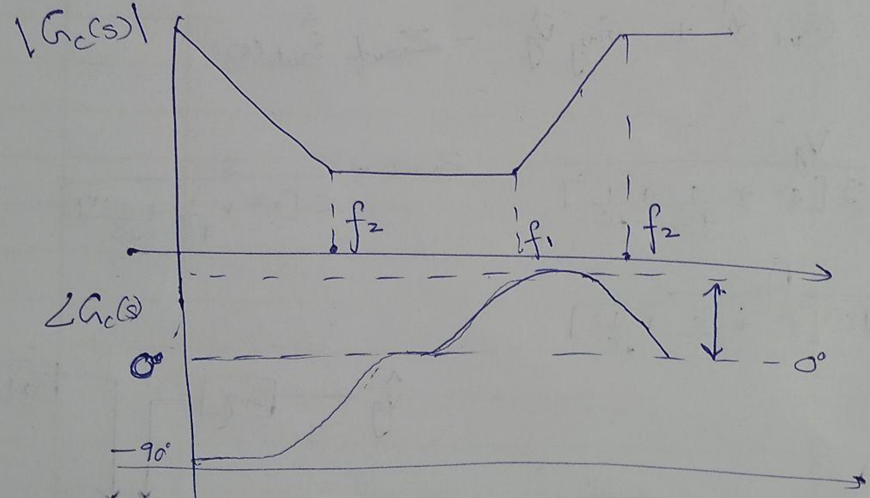
$$\|T\| = -22.133\ dB$$

$$\angle T(s) = -168.66° \quad @\ 40KHz.$$

For zero steady state error

introduce a pole at $s=0$.

Let $G_c(s) = k\left[1 + \frac{\omega_z}{s}\right]\left[\frac{s+\omega_1}{s+\omega_2}\right]$



We want $48°$ gain at $40KHz = 1/T$

so $f_1 f_2 = (40KHz)^2$

& let $a = \frac{1+\sin(48°)}{1-\sin(48°)} \approx 6.8$

then $f_1 = \frac{1}{\sqrt{a}\,T}$ $\quad f_2 = \frac{\sqrt{a}}{T}$

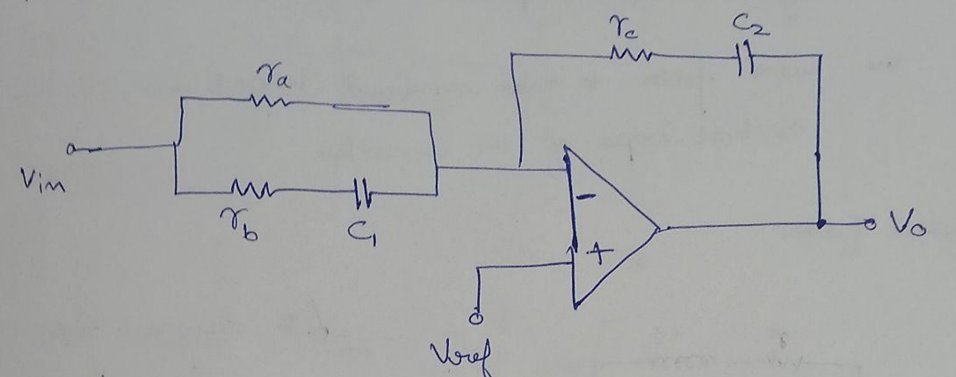
$\omega = 2\pi f$ $\quad \Rightarrow \quad f_1 = 15354\ Hz$

$f_2 = 104203\ Hz$

select $f_z << 40\,kHz$ to avoid phase lag by f_z

here so we choose $f_z = 2\,kHz$

Implementation.



For AC

$$\frac{V_o}{V_{in}} = \frac{\left(r_c + \frac{1}{sC_2}\right)}{r_a \parallel \left(r_b + \frac{1}{sC_1}\right)}$$

$$\cancel{r_c} = \left(\frac{r_c}{r_a \parallel r_b}\right)\left[1 + \frac{1}{sC_2 r_c}\right]\left[\frac{s + 1/[(r_a+r_b)C_1]}{s + 1/[r_b C_1]}\right]$$

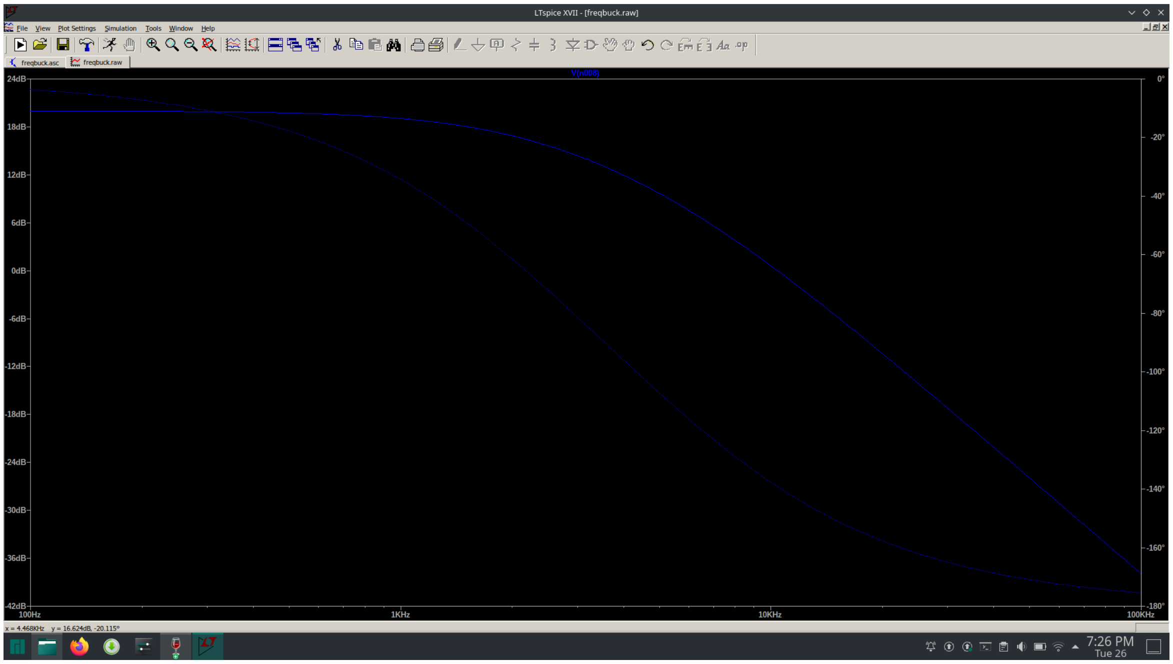
Plugging in values for required $G_c(s)$ we get (without adjusting gain yet)

$r_c = 6.1\,k\Omega$ $C_1 = 1.45\,nF$ $C_2 = 13\,nF$

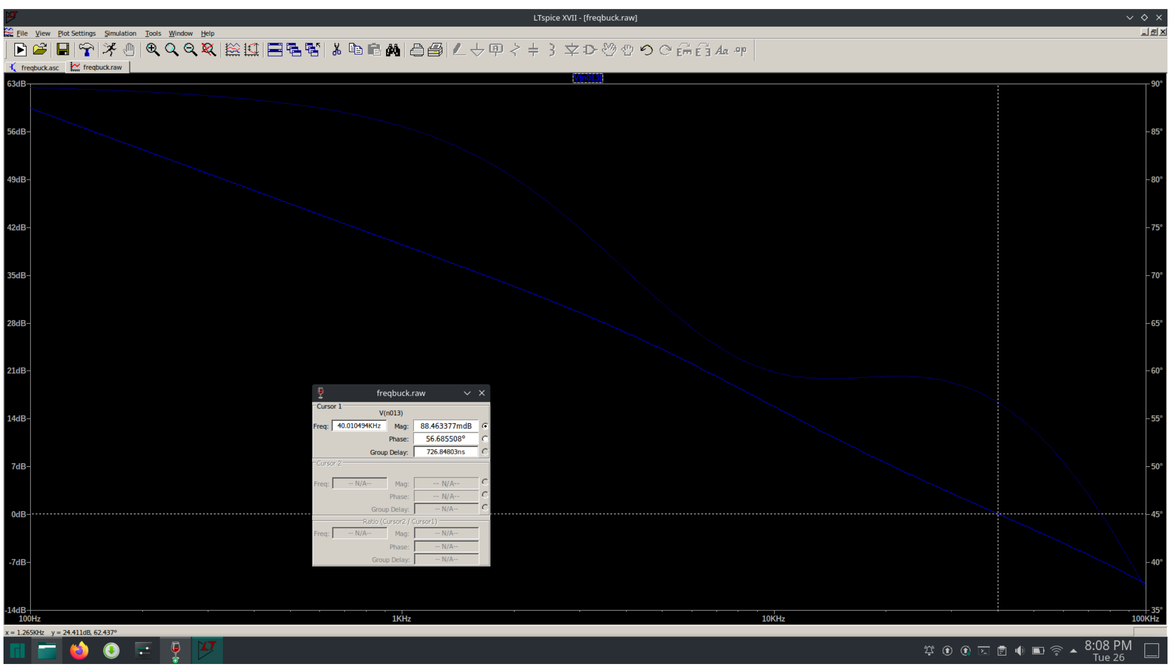
$r_a = 6.55\,k\Omega$ $r_c = 1\,k\Omega$

At last we add another gain stage. (also since it was inverting, so we need another inverting stage)

* The need to use ~~at~~ 2 stages arises due to finite GBW product of opamps.



Open Loop Transfer Function Uncompensated



Compensated open loop transfer function

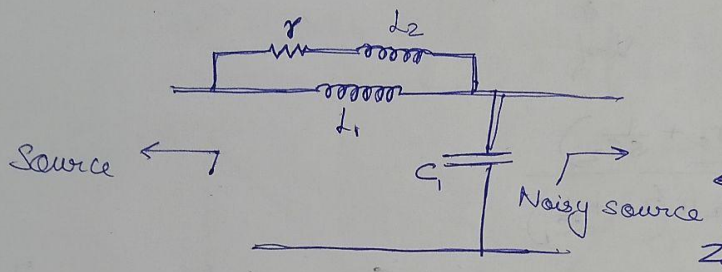
we get our G_c as required.

Now to design EMI Filter.

To design an active & passive EMI Filter.

we want filter to have minimal impact on control loops of the converter.

(1) Passive Filter.



Lets design for

−40 dB at 250 KHZ

Also $Z_{out}(s) << \frac{R}{D^2}$

(The detailed designed is skipped here, its based on Ch-17 of Fundamentals of Power Electronics by Erickson).

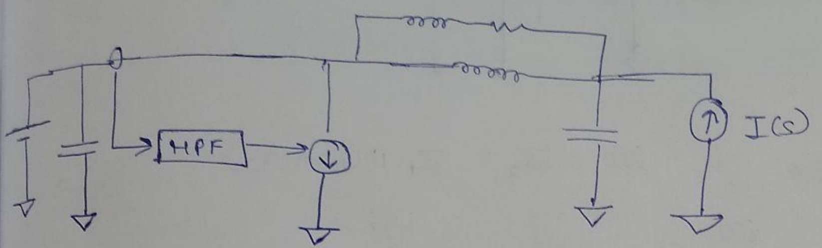
$L_1 = 5.5\mu H$ $L_2 = 2.55\mu H$ $C = 22\mu H$

$r = 0.5\Omega$

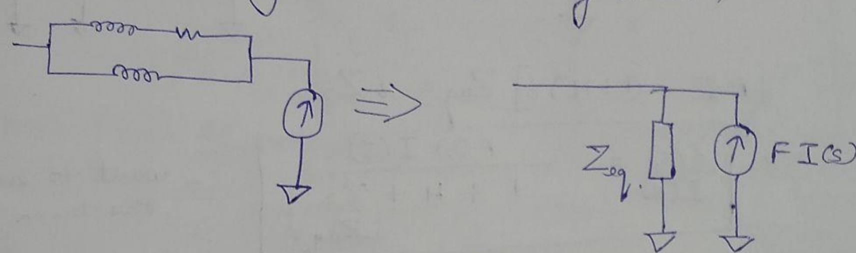
Design of active EMI Filter

Modelling.

The Buck Converter side can be modelled as a current source



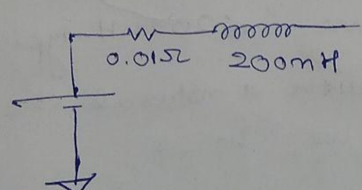
The current is sensed, then high pass filtered & ~~passed through~~ shunted to ground.



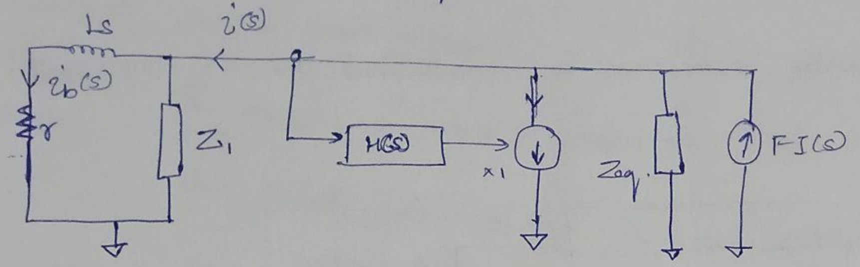
Norton Equivalent

At high freq. the input voltage source can be seen as zero impedance however parasitic inductances (we are concerned with 100 KHz > frequencies) are present.

So typical ~~values of~~ source at high freq.



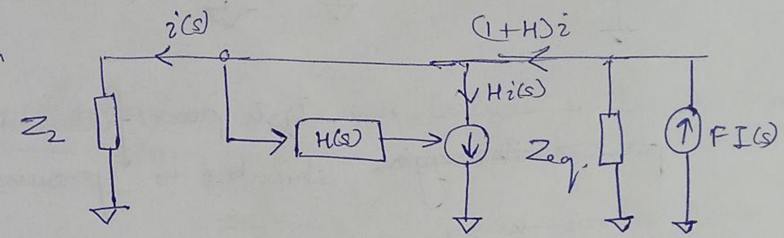
~~let~~ at high freq



$$i_b(s) = \frac{i(s) Z_1}{Ls + r}$$

let $Z_2 = Z_1 \parallel (Ls + r)$

then



$$[FI - (1+H)i] Z_{eq} = i Z_2$$

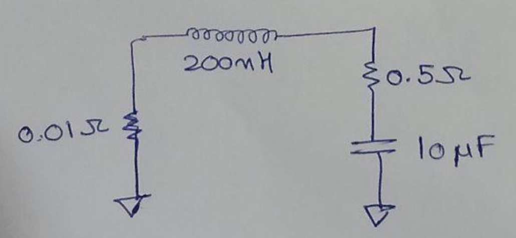
$$\Rightarrow \boxed{\frac{i(s)}{I(s)} = \frac{F(s)\, I(s)}{1 + H + \frac{Z_2}{Z_{eq}}}}$$

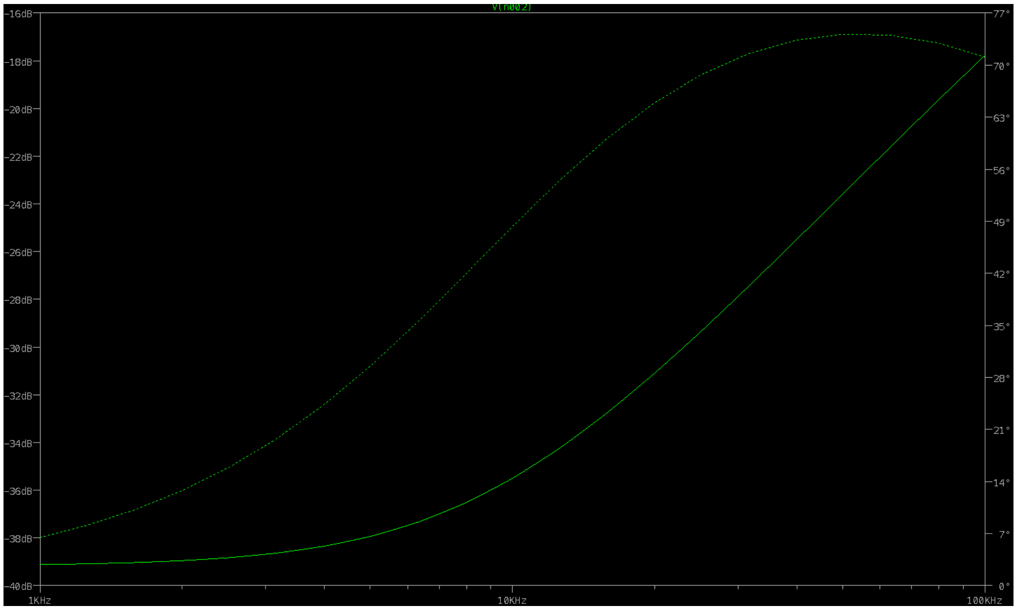
want to minimise this term.

$\frac{Z_2}{Z_{eq}}$ is a problematic term & can lead to stability problems so we want to minimise it. so that $\frac{Z_2}{Z_{eq}} << 1$ for lower freq.

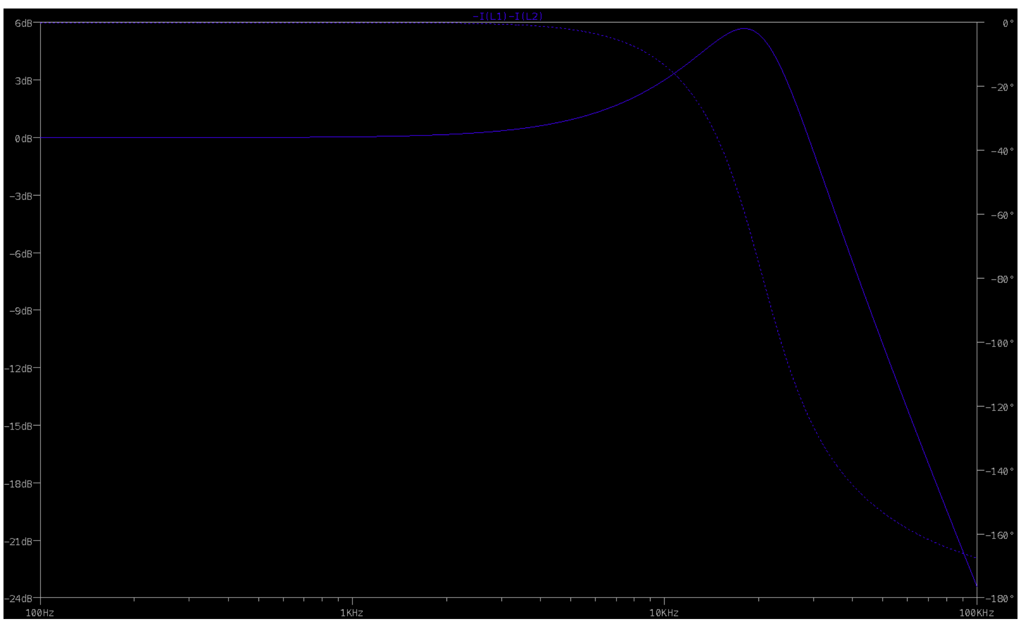
& design of H(s) becomes easier.

the parasitic inductance ($\leq$ 200mH typical) can cause resonance with a natural choice of Z_1 as capacitor so we choose.




V(n002)
-16dB
-18dB
-20dB
-22dB
-24dB
-26dB
-28dB
-30dB
-32dB
-34dB
-36dB
-38dB
-40dB
77°
70°
63°
56°
49°
42°
35°
28°
21°
14°
7°
0°
1KHz
10KHz
100KHz

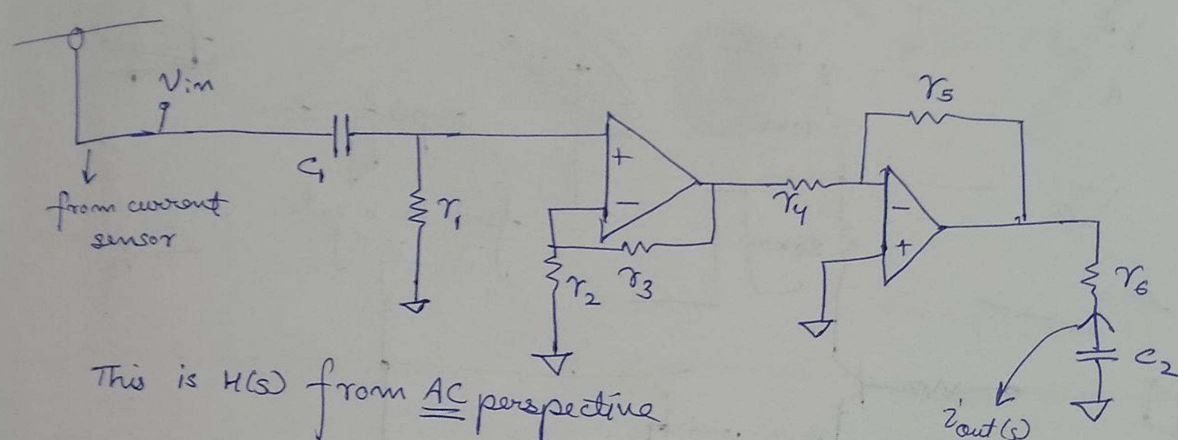
Z2


-I(L1)-I(L2)
6dB
3dB
0dB
-3dB
-6dB
-9dB
-12dB
-15dB
-18dB
-21dB
-24dB
0°
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
100Hz
1KHz
10KHz
100KHz

F(s)

I(s) has ~~so~~ components at switching frequencies & its multiples only. so a slight dip therefore isn't a problem in F(s) at lower frequencies...

let H(s) be 2nd order High Pass filter.
(actually its a Voltage to current converter)

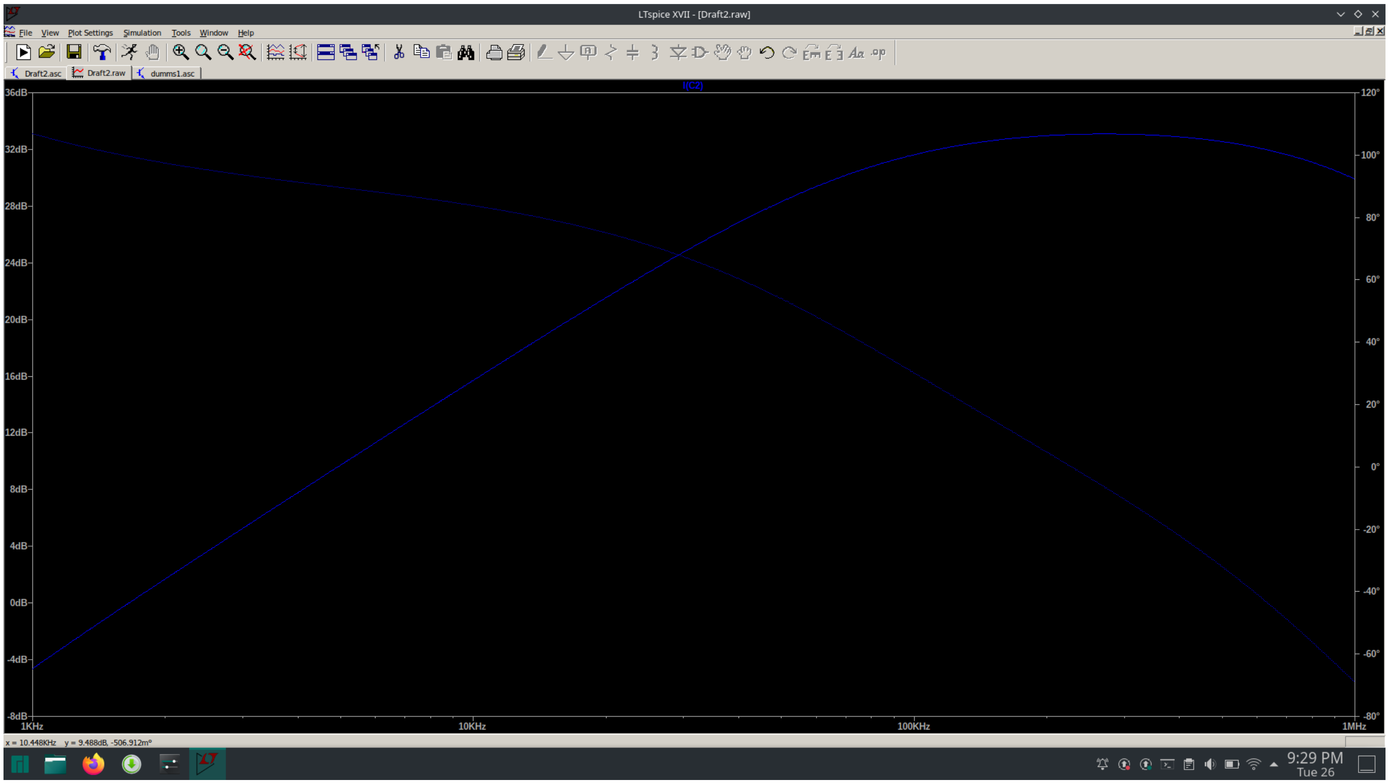


This is H(s) from AC perspective.

$$\frac{i_{out}(s)}{V_{in}(s)} = \frac{1}{r_6}\left(\frac{r_5}{r_4}\right)\left(1+\frac{r_3}{r_2}\right)\left(\frac{s^2}{\left(s+\frac{1}{r_1C_1}\right)\left(s+\frac{1}{r_6C_2}\right)}\right)$$

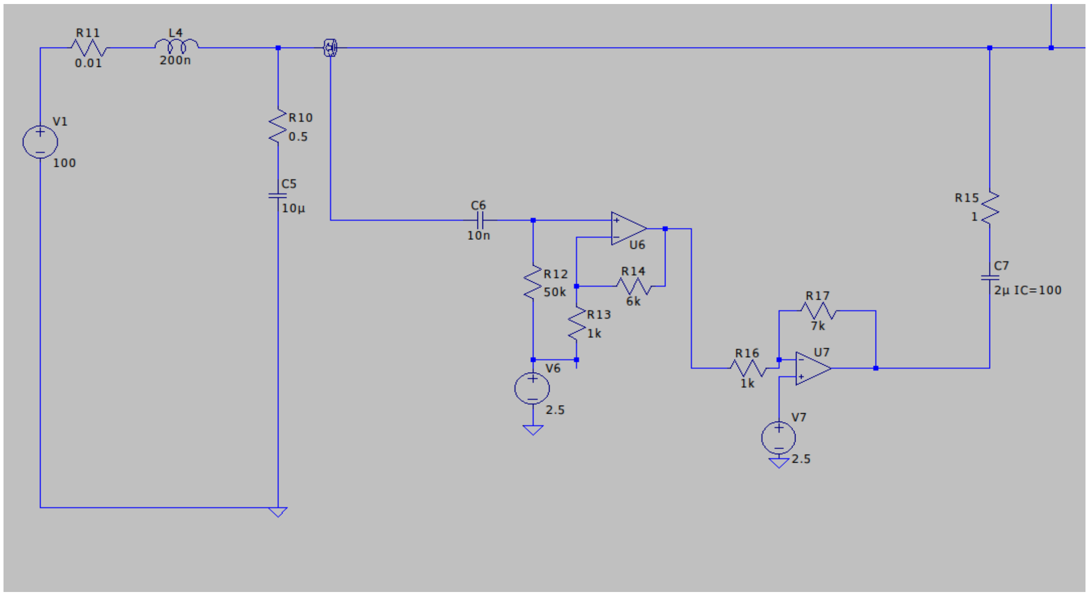
we can play around with these values but must ensure stability & sufficient gain to suppress EMI.

In this example. $C_1 = 10mF$ $r_1 = 50k\Omega$ $r_3 = 6k\Omega$
$r_2 = 1k\Omega$
$r_5 = 7k\Omega$ $r_4 = 1k\Omega$
$C_2 = 2\mu F$ $r_6 = 1\Omega$.

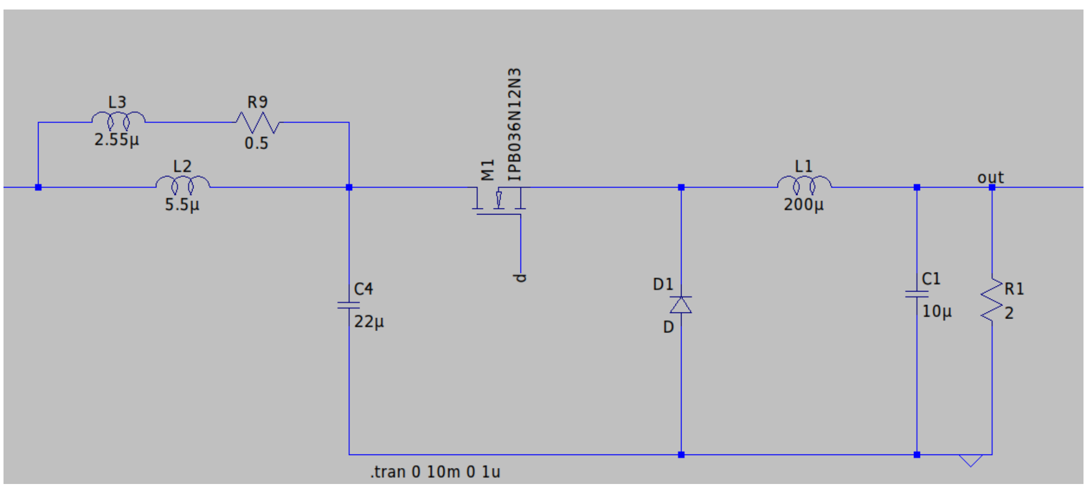


The high pass filter, the above plot is for output current vs input voltage iout(s)/vin(s)

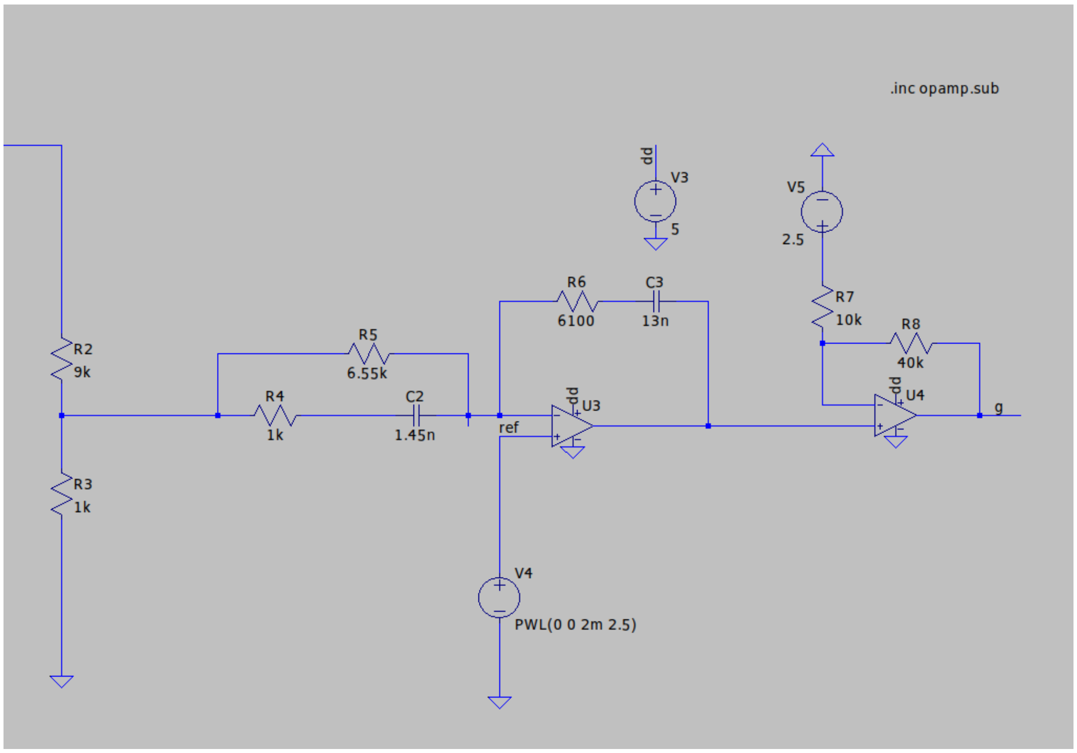
The complete circuit



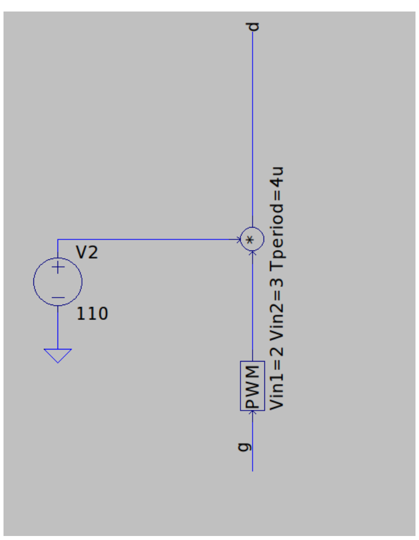
The input voltage source and Z2 and active EMI filter



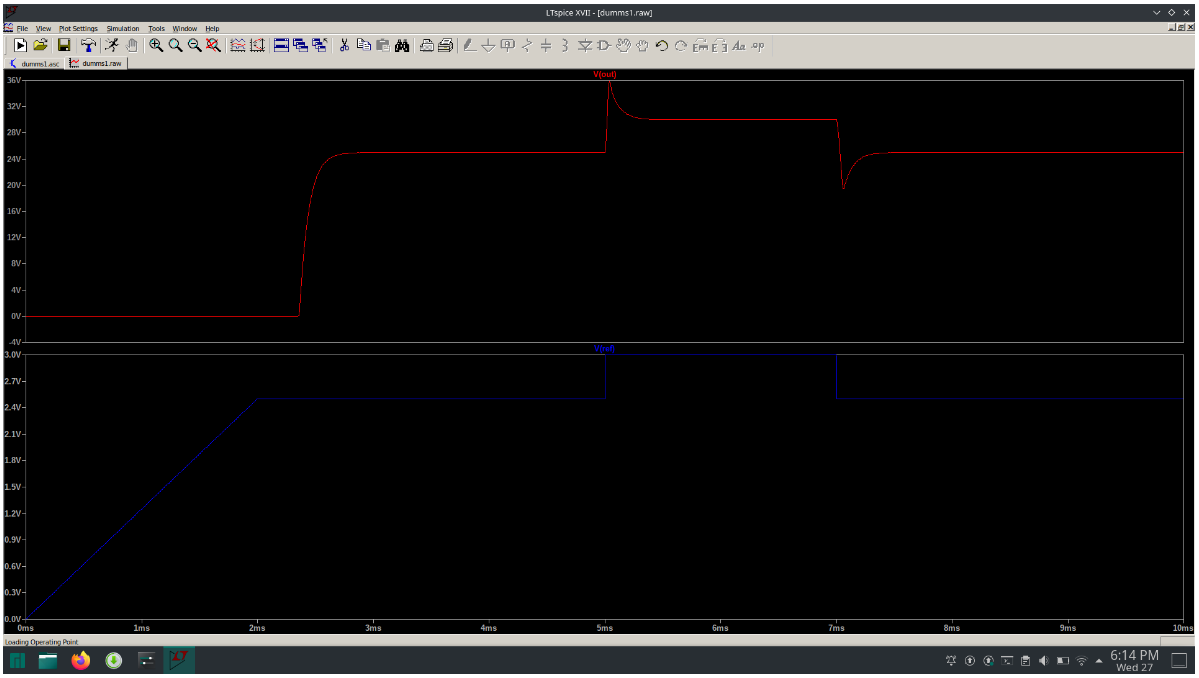
Passive EMI filter and Buck converter



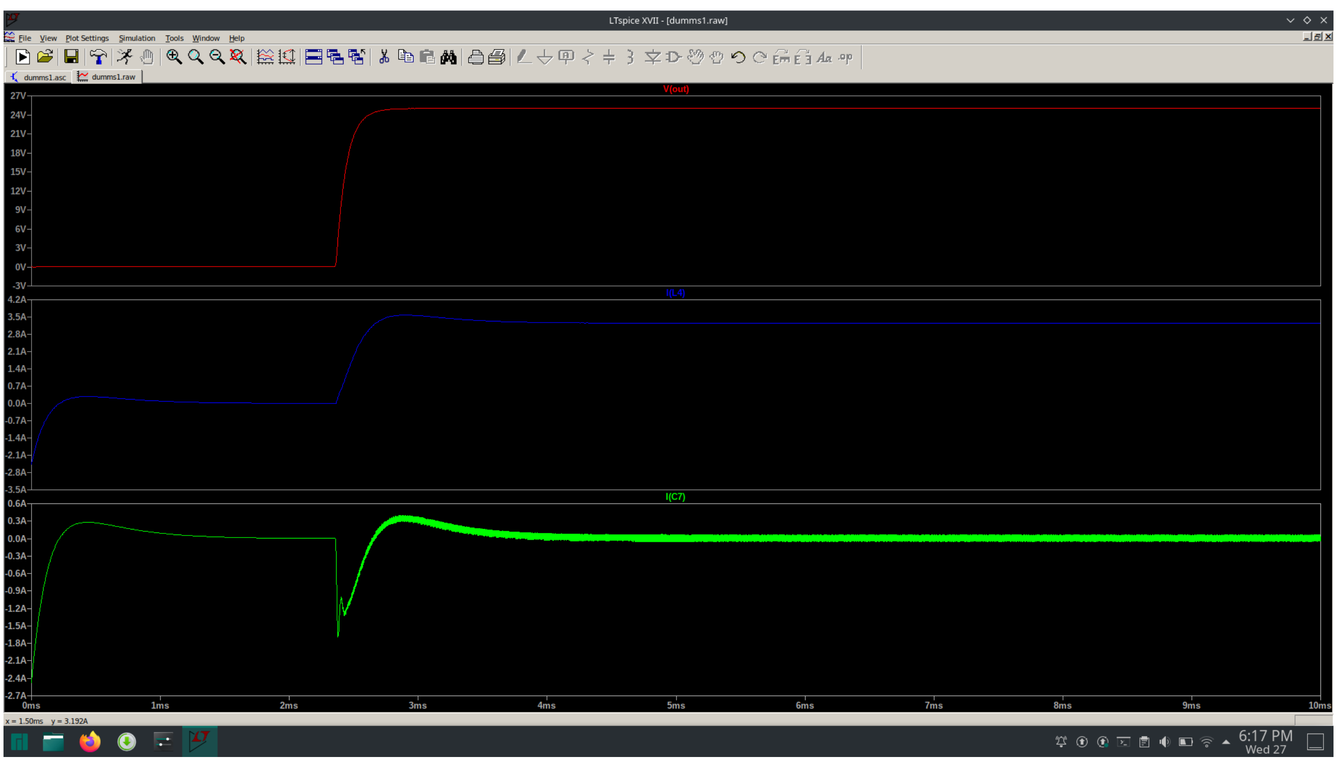
The closed loop controller



PWM block form the library



Output Voltage vs reference (soft start to avoid initial overvoltage at input)



The currents, Blue waveform -> Battery current (very clean)!, Green waveform -> the current though the active EMI filter, the high frequency components are shunted by active EMI filter, red curve is output voltage