FINAL PROJECT

Final project

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This Report is as a final project for power electronics course REE 411 for Renewable energy engineering course. The project is about building a buck-boost converter that is capable of operating between voltage limits of 12 and 24 V.

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Introduction:

Every electronic device consists form different components that operates under specific conditions for the voltage and current and since the voltage sources at homes are about 220/240 V so its critical to keep electronic devices work efficiently and save power, and one of the most important applications is the Buck-Boost converter. A converter capable of stepping down/up the voltage via certain mechanism in order to achieve optimum power deliver to the load. Buck-Boost converter is converter configuration of electrical elements such inductor, capacitor, and switching elements like Mosfet and diode, each component has his own ratings and specifications.

Problem definition:

Design a Buck-Boost converter that have the following criteria:

$$\Delta i_L < 40\%\ I_L$$

$$\Delta v_0 = 250\ mV$$

Continuous conduction mode

Assumptions:

1- Continuous conduction mode.
2- Ideal switching components (Diode, Mosfet)
3- Ideal inductor and capacitor (No internal resistances)

DC-Analysis

A Buck-Boost converter.

$$\frac{v_g DT}{L} = \Delta i_{L,off}$$

$$\Delta i_{L,on} = \frac{V_o(1-D)T}{L}$$

$$\Delta i_{L,on} + \Delta i_{L,off} = 0$$

$$V_o = -V_s\left(\frac{D}{1-D}\right)$$

- The negative value is for the polarity of the load.

Bucking situation:

$$v_g = 24\ V$$

$$v_o = 12\ V$$

$$I_o = 2\ A$$

So, the Load value $\frac{v_o}{I_o} = 6\ \Omega$

The Duty ratio $D = \frac{v_o}{v_o + v_g} = 0.333$

Boost Situation

$$v_g = 12\ V$$

$$v_o = 24\ V$$

$$I_o = 1\ A$$

So, the Load value $$\frac{v_o}{I_o} = 24\ \Omega$$

The Duty ratio D = $\frac{v_o}{v_o+v_g}$ = 0.6667

Calculating the inductance and the capacitance:

$$v_g I_g = v_o I_o$$

$$I_g = D I_L$$

$$I_L = \frac{v_o I_o}{v_g D}$$

$$I_o = \frac{v_o}{R}$$

So

$$I_L = \frac{{v_o}^2 D}{R(1-D)}$$

$$\Delta i_L = \frac{v_g\ DT}{L}$$

Let the switching frequency $f = 50\ K\ Hz$, R= 24 Ω

So, $$I_L = 3\ A$$

$$\Delta i_L = 1.2\ A$$

$$I_{max} = 3.6\ A$$

$$I_{min} = 2.4\ A$$

To calculate the minimum inductance required for Continues conduction current operation, Choose R= 24 Ω, D= 0.6663, and use safety factor of 1.25

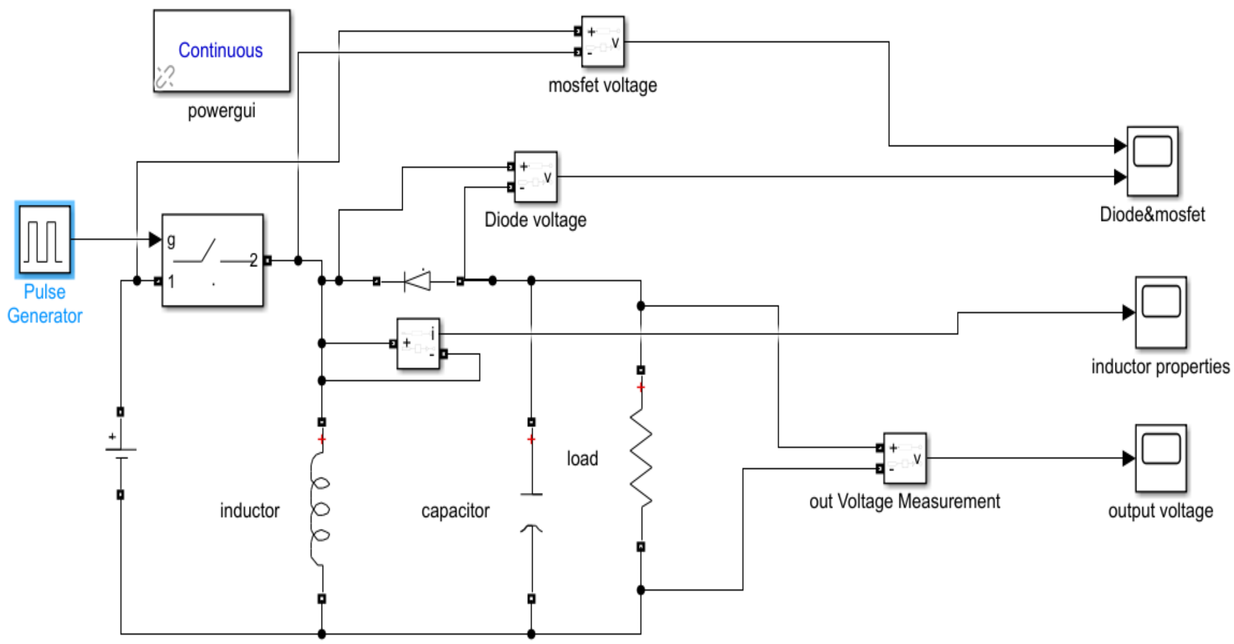
$$L_{min} = \frac{(1-D)^2 R}{2f} * 1.25$$

$$L_{min} = 3.33 * 10^{-5}\ H$$

The capacitance:

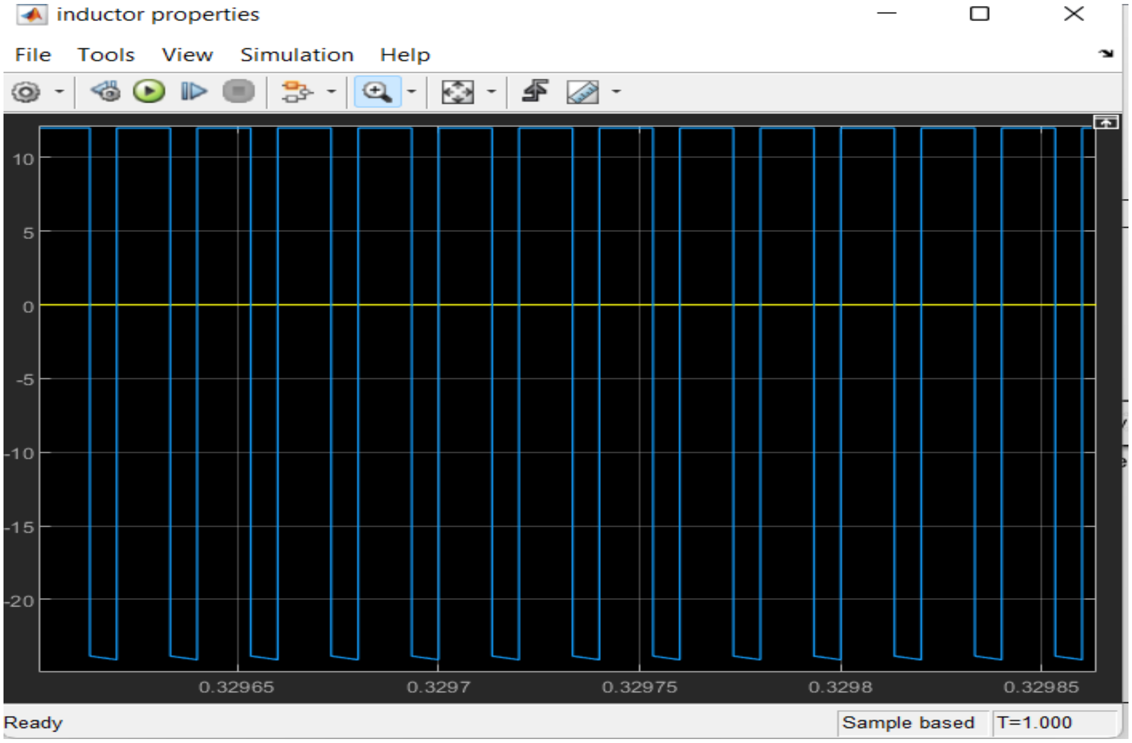
$$C = \frac{D}{Rf\frac{\Delta v_O}{v_O}} = 5.33 * 10^{-5}\ \text{F}$$

The waveforms of the converter.

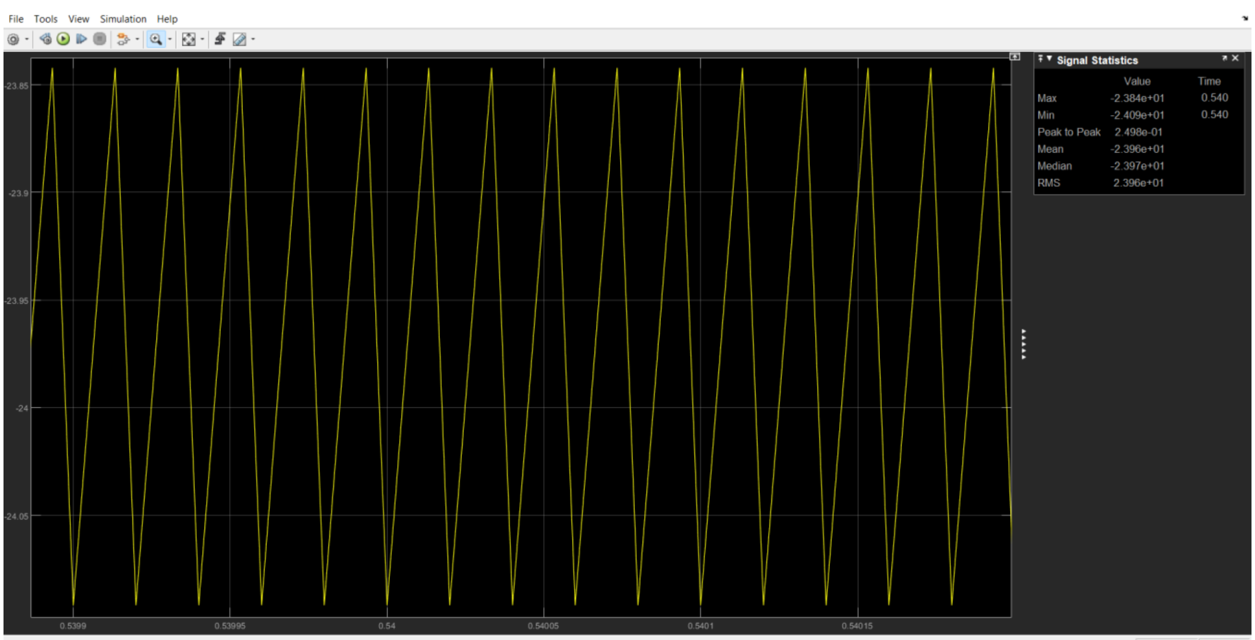


The configuration as a whole, with the previous components' values, the waveforms will be as follows:

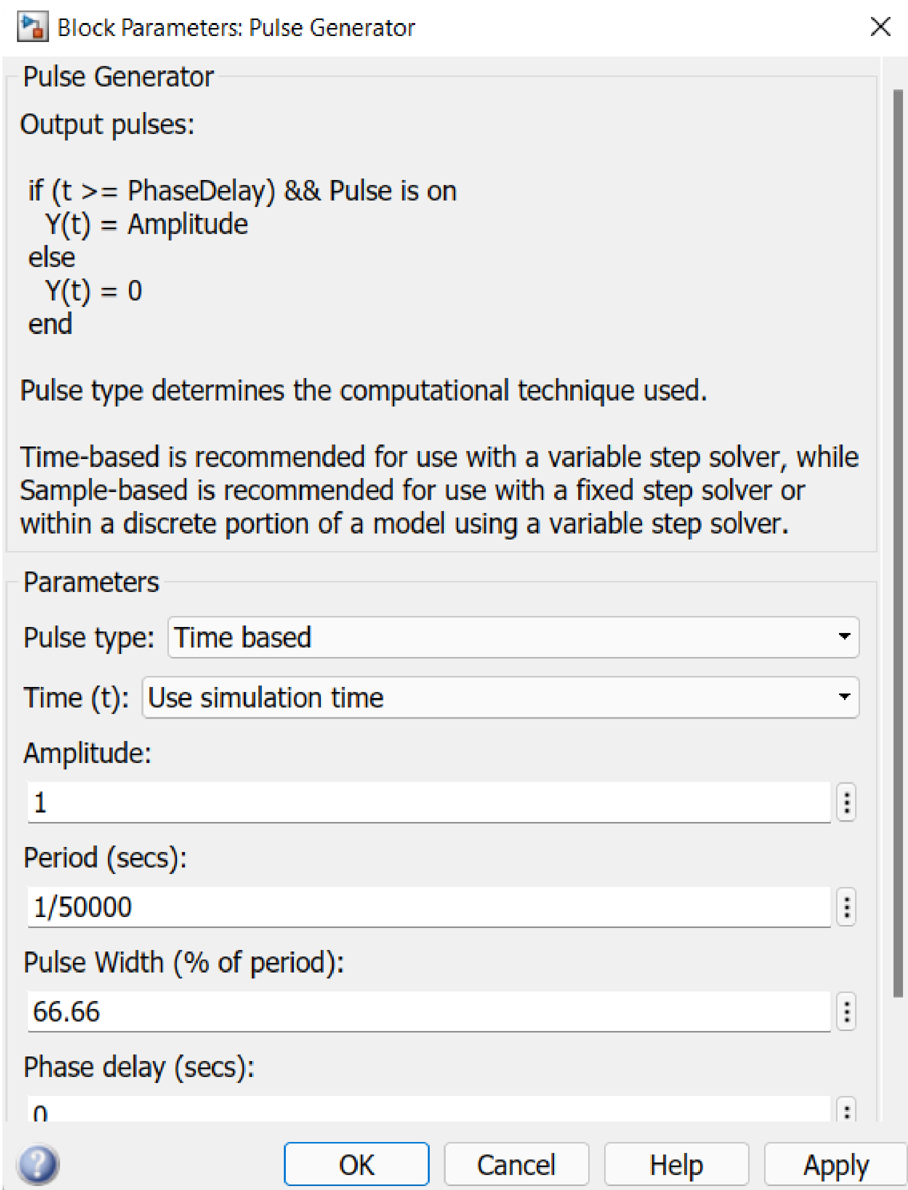
Inductor voltage



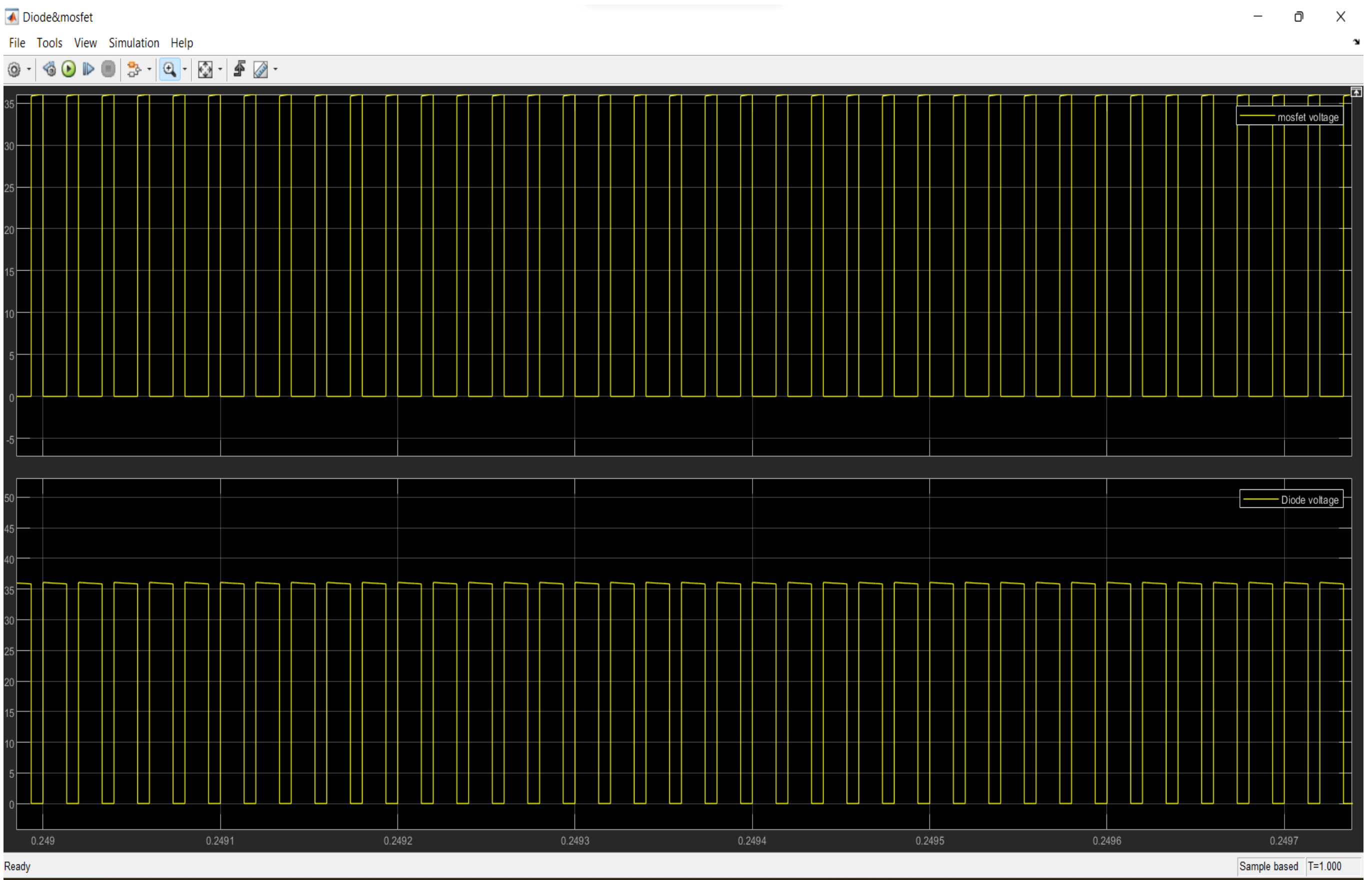
Output voltage



Pulse generator to generate the switching waveform before adding the control system.



Diode and MOSFT voltages



- Maximum voltage and current for the MOSFET.

Maximum current for the MOSFT is equivalent to the maximum inductor current:

$$I_{Q,max} = I_{max} = 3.6\ A$$

Maximum voltage will be during the buck operation which will be 24V.

Selection of suitable MOSFET:

Suggested MOSFET

- IRF4905(Rejected)
  - It is P-channel with $V_{DSS} = -55$ V
- 2SK2998(Rejected)

- It has on Resistance 10.5 ohm & V_{DSS}=500 V

- IRF540N (Accepted)
  - It has low R_{on} =0.04 ohm & V_{DSS}=100 V
- STR2N2VH5) Rejected):
  - V_{DS} = 20 V

Therefore, IRF540N type has the smallest on resistance, the more suitable voltage, and it's available at the lab.

Selection of suitable Diode:

- 1N4740A(Rejected)
  Zener diode with Vmax = 10.5 v
- RUR15100(Rejected)
  V_{RRM}=1000 v &I_F =15A & V_F = 1.5
- 1N5817(Rejected)
  V_{RRM}=20 v &I_F =3A & V_F =0.75
- BA159(Accepted)
  V_{RRM}=1000 v &I_F =1A & V_F = 1.3

Therefore (BA159) has the smallest V_F so smallest power loss & the more suitable voltage but it's not available at the lab so we use the available one (IN4007) which has V_{RRM}=1000 v & V_F= 1v& I_F = 1A

AC-Analysis

For this type of analysis, we actually discover how the input voltage, Duty cycle, output current, and output voltage varies with time, in other words, the Duty cycle is not constant as we are assuming, it has a dc component and another Ac component and the same applies to other variables so in this section we are going to introduce the Ac analysis for Buck-Boost converter to get the transfer function and use it in order to improve the performance of the converter using PI controller.

Firstly, we use the perturbation method for conducting the AC analysis, this method is used in order to linearizing the equations that describes the converter.

Starting with stating the assumptions of the analysis:

$$\langle i(t)\rangle_{T_s} = I + \hat{\imath}(t)$$
$$\langle v(t)\rangle_{T_s} = V + \hat{v}(t)$$
$$\langle i_g(t)\rangle_{T_r} = I_g + \hat{\imath}_g(t)$$
$$\langle v_g(t)\rangle_{T_s} = V_g + \hat{v}_g(t)$$
$$d(t) = D + \hat{d}(t)$$

- Parameters between brackets are the average values over the cycle.
- The capital variables are the DC components and the variables with "hat" are the AC Components.
-

$$d'(t) = (1 - d(t)) = 1 - (D + \hat{d}(t)) = D' - \hat{d}(t)$$
$$D' = 1 - D$$

$$L\frac{d(I + \hat{\imath}(t))}{dt} = (D + \hat{d}(t))\big(V_g + \hat{v}_g(t)\big) + \big(D' - \hat{d}(t)\big)(V + \hat{v}(t))$$

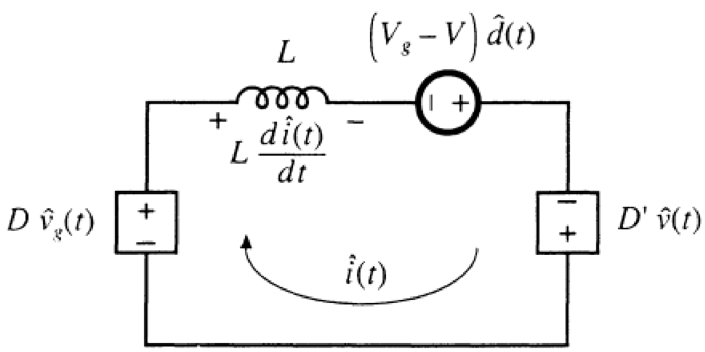
$$L\left(\frac{dI}{dt}+\frac{d\hat{\imath}(t)}{dt}\right)=\underbrace{\left(DV_g+D'V\right)}_{\text{Dc terms}}+\underbrace{\left(D\hat{v}_g(t)+D'\hat{v}(t)+\left(V_g-V\right)\hat{d}(t)\right)}_{1^{st}\text{ order ac terms (linear)}}+\underbrace{\hat{d}(t)\left(\hat{v}_g(t)-\hat{v}(t)\right)}_{\substack{2^{nd}\text{ order ac terms}\\ \text{(nonlinear)}}}$$

- The Dc terms will be cancels out since they equal to 0 over the period
- The Nonlinear terms (they are product of multiplying two-time variant quantities) will cancels out.
- The only remaining terms are the linear terms and they will be used to build the equivalent circuit.

The final equation for the voltage across the inductor will be as follows:

$$L\left(\frac{d\hat{\imath}(t)}{dt}\right)=\underbrace{\left(D\hat{v}_g(t)+D'\hat{v}(t)+\left(V_g-V\right)\hat{d}(t)\right)}_{1^{st}\text{ order ac terms (linear)}}$$

this is the equivalent circuit for the voltage across the inductor.



Following the same approach for the current across the capacitor

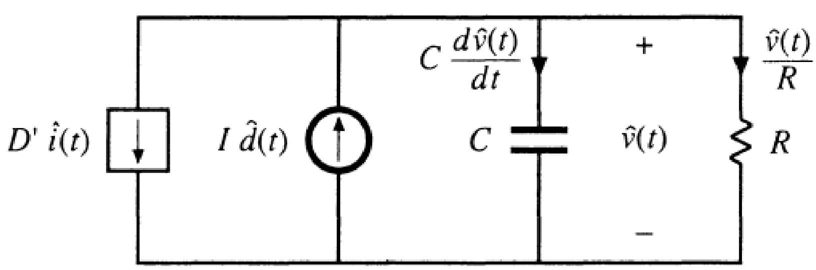
$$C\frac{d(V+\hat{v}(t))}{dt} = -\left(D' - \hat{d}(t)\right)(I+\hat{\imath}(t)) - \frac{(V+\hat{v}(t))}{R}$$

$$C\left(\frac{dV}{dt}+\frac{d\hat{\hat{v}}(t)}{dt}\right) = \underbrace{\left(-D'I-\frac{V}{R}\right)}_{\text{Dc terms}} + \underbrace{\left(-D'\hat{\imath}(t)-\frac{\hat{v}(t)}{R}+I\hat{d}(t)\right)}_{1^{st}\text{ order ac terms}} + \underbrace{\hat{d}(t)\hat{\imath}(t)}_{\substack{\text{(linear)}\\ 2^{nd}\text{ order ac term}\\ \text{(nonlinear)}}}$$

- The Dc terms will be cancels out since they equal to 0 over the period
- The Nonlinear terms (they are product of multiplying two-time variant quantities) will cancels out.
- The only remaining terms are the linear terms and they will be used to build the equivalent circuit.

Apply the pervious conditions to produce the equation for current across the capacitor

$$C\left(\frac{dV}{dt}\right) = \underbrace{\left(-D'\hat{\imath}(t)-\frac{\hat{v}(t)}{R}+I\hat{d}(t)\right)}_{1^{st}\text{ order ac terms}}$$



Apply the same approach for the input current:

$$I_g + \hat{\imath}_g(t) = (D+\hat{d}(t))(I+\hat{\imath}(t))$$

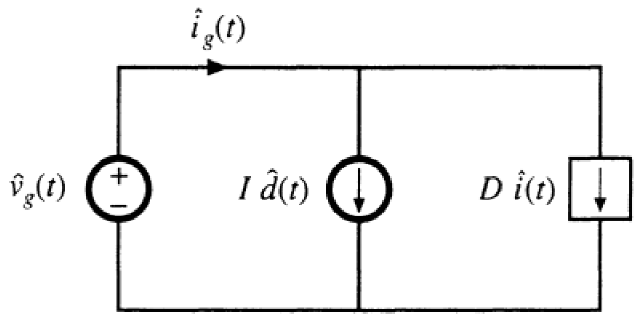
$$\underbrace{I_g}_{\text{Dc term}} + \underbrace{\hat{\imath}_g(t)}_{1^{st}\text{ order ac term}} = \underbrace{(DI)}_{\text{Dc term}} + \underbrace{(D\hat{\imath}(t)+I\hat{d}(t))}_{1^{st}\text{ order ac terms}} + \underbrace{\hat{d}(t)\hat{\imath}(t)}_{\substack{\text{(linear)}\\ 2^{nd}\text{ order ac term}\\ \text{(nonlinear)}}}$$

- The Dc terms will be cancels out since they equal to 0 over the period
- The Nonlinear terms (they are product of multiplying two-time variant quantities) will cancels out.
- The only remaining terms are the linear terms and they will be used to build the equivalent circuit.

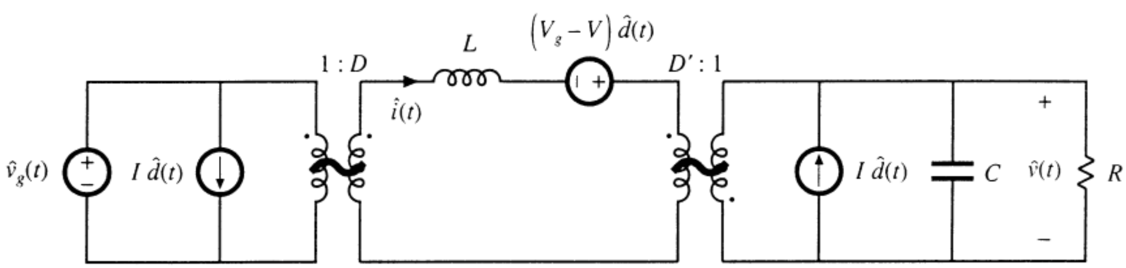
Applying the previous conditions,

$$\underbrace{\hat{\imath}_g(t)}_{1^{st}\text{ order ac term}} = \underbrace{(D\hat{\imath}(t) + I\hat{d}(t))}_{1^{st}\text{ order ac terms}}$$

And the equivalent circuit is:



Now it is time to combine the 3 circuits into one equivalent circuit that represents the converter.



Transfer functions

So, to get the transfer functions,

We shall do the following:

1- Decide which ratio of parameters I need and eliminates other sources, It is like using the superposition principle.

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Starting with $\frac{\hat{v}}{\hat{v}_g}, So\ \hat{d} = 0$

So, the equivalent circuit get reduced, a good knowledge of transformers will help in combining the reduced model into one circuit and then, the transfer function will be as follows:

A lot of algebra operations have been used to simplify the transfer function.

$$\frac{\hat{v}}{\hat{v}_g} = \frac{-D}{D'}\left(\frac{1}{1 + \frac{sL}{R(D')^2} + \frac{s^2 * L * c}{(D')^2}}\right)$$

Using the superposition principle to get $\frac{\hat{v}}{\hat{d}}$ .Doing the previous operations to get and simplify the transfer function.

$$\frac{\hat{v}}{\hat{d}} = \frac{(v_g - v)}{(D')^2} * \left(\frac{1 - s\frac{LI}{v_g - v}}{1 + \frac{sL}{R(D')^2} + \frac{s^2 * L * c}{(D')^2}}\right)$$

Comments on the terms of the $\frac{\hat{v}}{\hat{d}}$ transfer function.

$1 - s\frac{LI}{v_g - v}$ $\Rightarrow$ This is a zero which is equivalent to $1 - \frac{s}{w^2}$

$\frac{L}{R(D')^2} \Rightarrow \frac{2\xi}{\omega_o}$, where ξ is the damping ratio, ω_o is the angular corner frequency

$\frac{(v_g - v)}{(D')^2}$ $\Rightarrow$ this is the gain of the transfer function.

$\frac{L*c}{(D')^2} = (\frac{1}{\omega_o})^2$ $\Rightarrow$the characteristics of the transfer function depends on the Duty ratio.

Using the superposition principle to get $\frac{\hat{v}}{\hat{I}_o}$. Doing the previous operations to get and simplify the transfer function.

$$\frac{\hat{v}}{\hat{I}_o} = \frac{RLs}{Ls + (D')^2RLCs^2 + \frac{R}{(D')^2}}$$

I have tried with this transfer function and this is what I have gotten

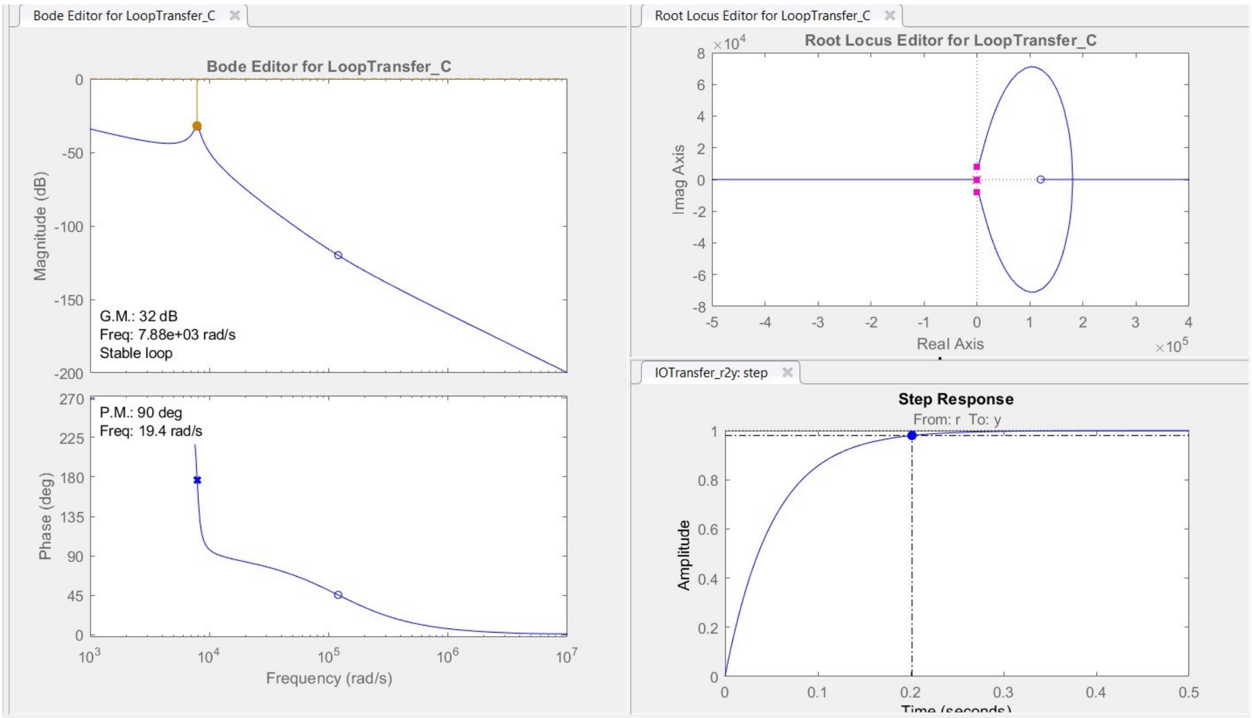
Designing a PI controller Use sisotool in MATLAB

Target is achieving the following: OS ≤ 4%, t_0 =20ms.

First, we use the following transfer function:

```
        -2.634e-05 s + 3.16
  ------------------------------------
  1.264e-08 s^2 + 9.877e-06 s + 0.7901
```

Then launch sisotool to find the bode plot, root locus and step response

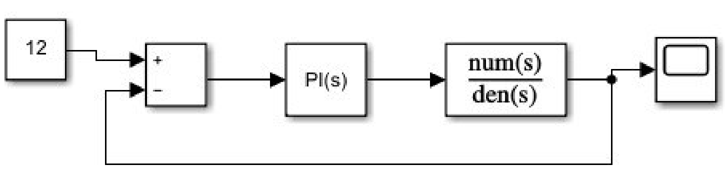


There are two roots on the imaginary axis which indicates that the system is critically stable

We need to get the values of P and I in order to design the PI controller. We found that our target is achieved when P=0 AND I=4.9. The resulted settling time is 200ms and 4% overshoot.

- The proportional gain shouldn’t equal to zero but we have done our best.

Then we make sure from our results by building the following Simulink blocks



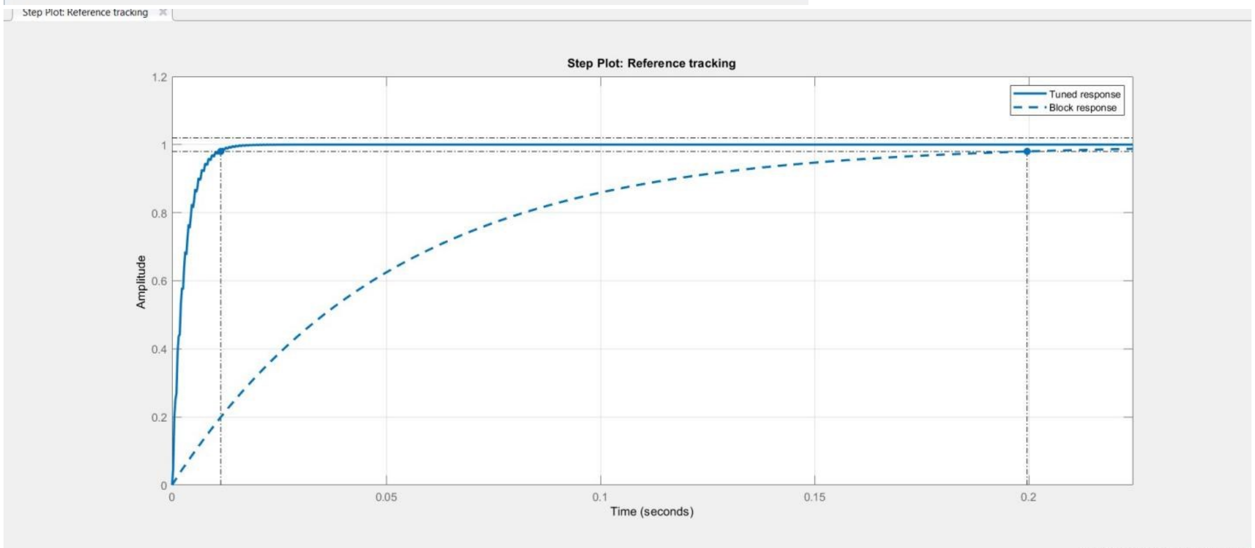
The result is the plot and the parameters of the simulation which are:

Controller Parameters

	Tuned	Block
P	0	0
I	88.9922	4.9
D	n/a	n/a
N	n/a	n/a

Performance and Robustness

	Tuned	Block
Rise time	0.0058 seconds	0.112 seconds
Settling time	0.0114 seconds	0.2 seconds
Overshoot	0.00753 %	0 %
Peak	1	1
Gain margin	6.77 dB @ 7.88e+03 ra...	32 dB @ 7.88e+03 rad/s
Phase margin	89.6 deg @ 357 rad/s	90 deg @ 19.6 rad/s
Closed-loop stability	Stable	Stable



The overshoot is relatively low but any change in the system will not have the same settling time.

Transfer functions with ESR with the capacitor.

Doing the same approach of reaching the equivalent circuit in order to get the transfer functions but this time will add a series resistance with the capacitor and here are the transfer functions.

The super position principle applies here also.

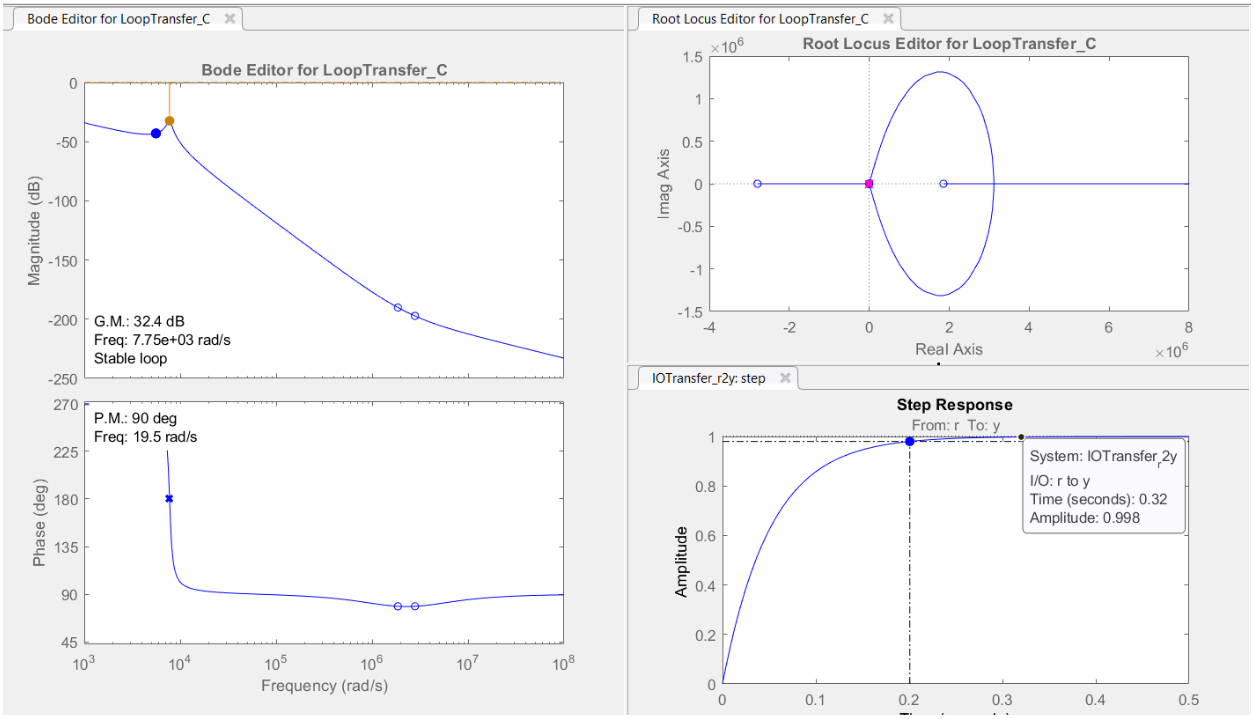
$$\frac{\hat{v}}{\hat{v}_g} = \frac{-D}{D'} * (\frac{Esr + R + RC}{R + s^2(\frac{LRC}{(D')^2} + \frac{LC * Esr}{(D')^2}) + s(\frac{L}{(D')^2} + RC * Esr)})$$

$$\frac{\hat{v}}{\hat{d}} = \frac{-(v_g - v)}{(D')^2} * \left(\frac{R + Esr * RC}{R + s\left(\frac{L}{(D')^2} + RC * Esr\right) + \ s^2\left(\frac{R * L * C}{(D')^2} + \frac{LC * Esr}{(D')^2}\right)}\right)$$

$$+I * (\frac{sL * (1 + Cs * Esr)}{s^2(2LC(R + Esr)) + s(L + Esr * RC * (D')^2) + (D')^2 * R}$$

$$\frac{\hat{v}}{\hat{I}_o} = \frac{sL * (1 + Cs * Esr)}{s^2(2LC(R + Esr)) + s(L + Esr * RC * (D')^2) + (D')^2 * R}$$

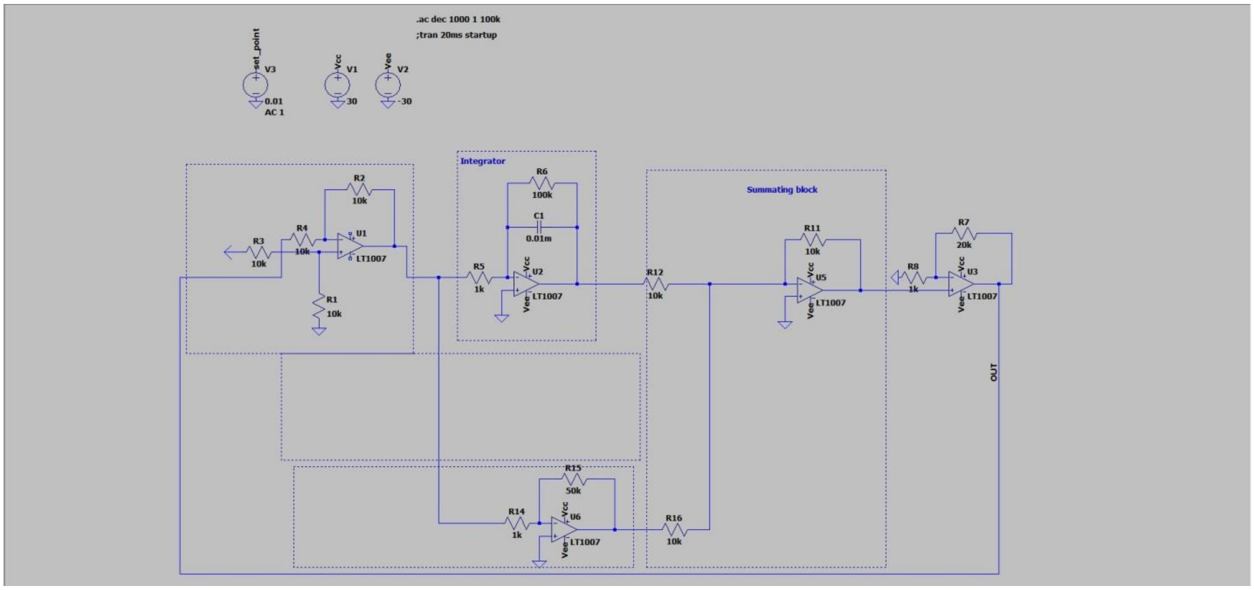
Using SISO tool to get the controller characteristics after adding the ESR with the capacitor.



- The Roots are on the zero point
- A zero on the left half plan is produced

Hardware

We have started by making the control circuit using Op-amps with the gains obtained from SISOtool , Here is the control circuit built in LTspice.



Then the hardware board is done with 3 inputs

1- Reference voltage

2- Sawtooth input

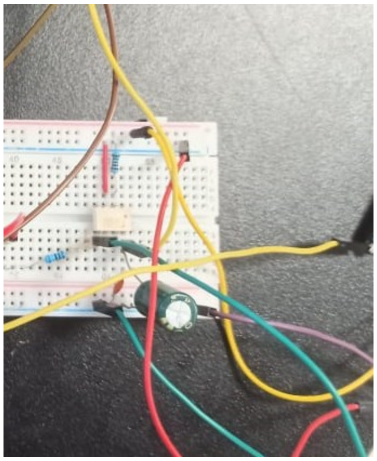
3- Vout of the converter

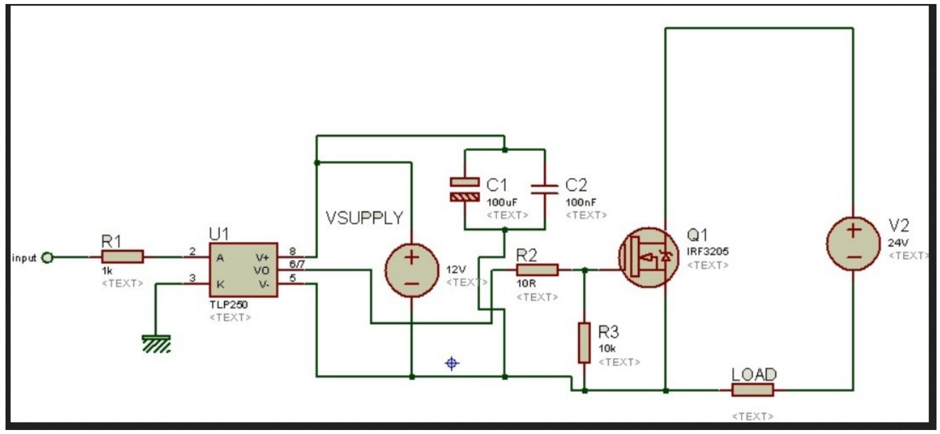
And one output which is the V out of the control circuit.

- We did not integrate the control circuit with the converter.

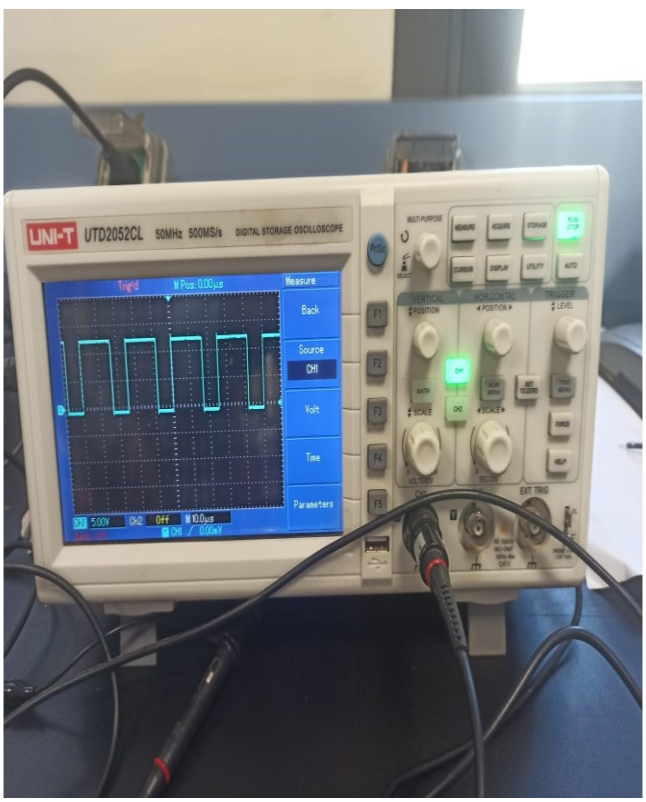
we have created the TLP250 circuit and obtained the signal from it which corresponds to the signal that controlling the MOSFET, the signals were semi-identical to each other.

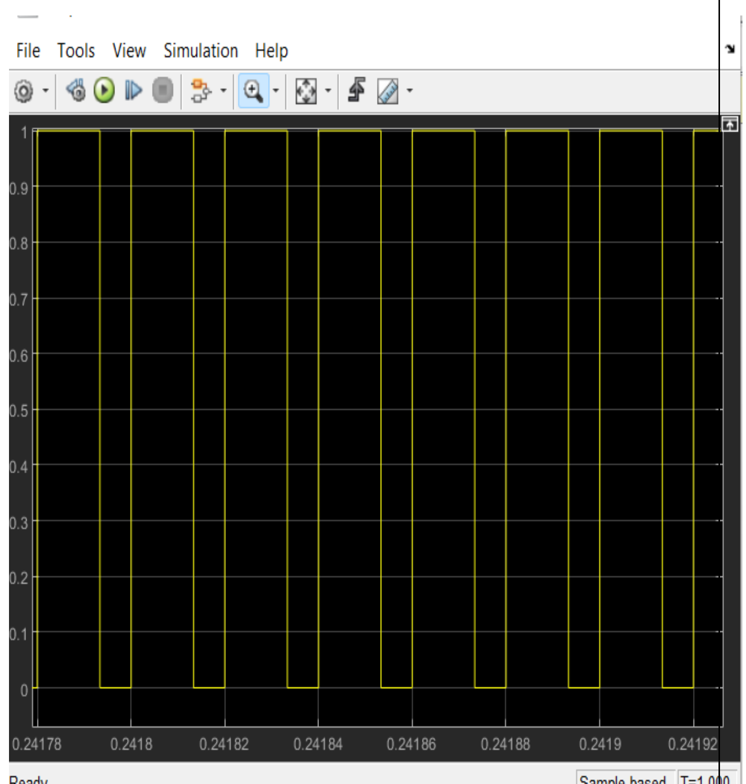
This is the TLP250 circuit that is used to drive the MOSFET.



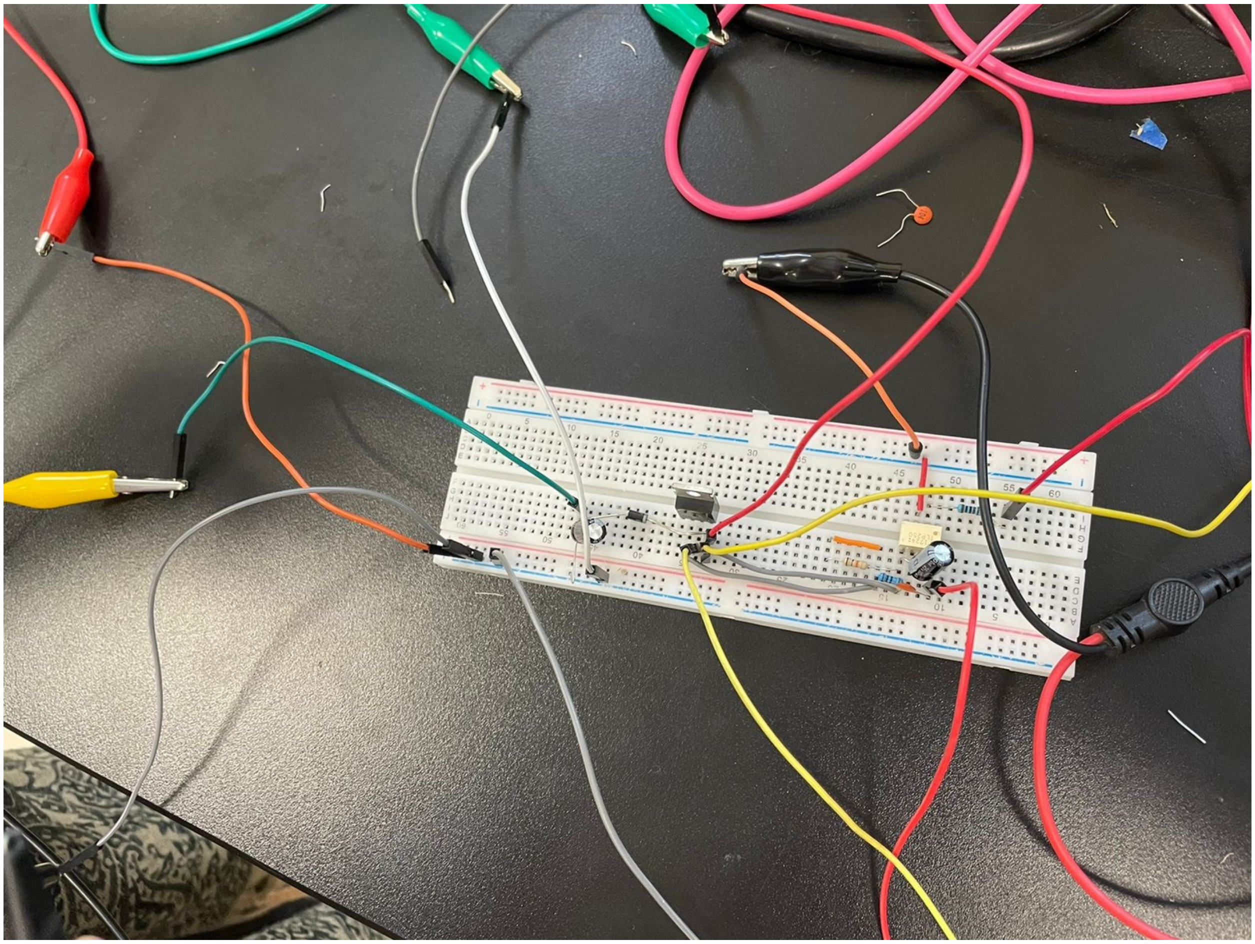


The signal from the driver circuit and the simulation in the Boosting mode with Duty = 0.66:





Here is a photo of the whole setup of the converter and the driver circuit.



The driver circuit is the circuit on the right half of the breadboard and on the left side is the converter. The Jumpers on the left side is used to map the load and the inductor to the board. The red jumper at the middle of the photo is used to transfer the output signal of the driver circuit to the gate of the MOSFET.

The green crocodiles are connected to the inductor.
The red and yellow crocodiles are connected to the load.

The converter has worked properly in both of the moods (Buck-Boost)

Bucking mood

Input voltage for the converter.

Input voltage for the MOSFET.

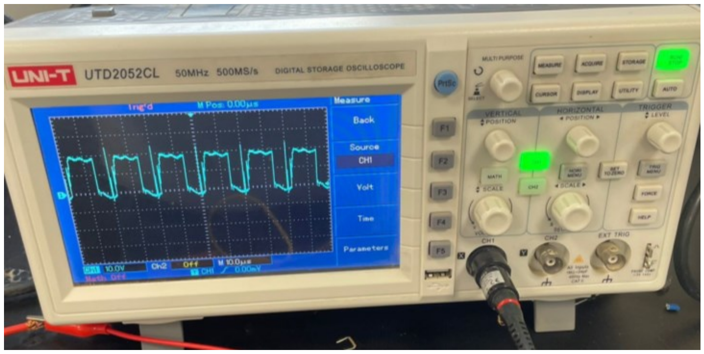
We have used separate voltage supplies for the converter and the MOSFET.

Duty

The Output voltage:

The output is 8.47 V, the input is 12 V
The expected voltage is 5.14 V

MOSFET drain-to-source wave



MOSFET: Gate to source wave.

The decaying in

the wave is because of the none ideality of the MOSFET.

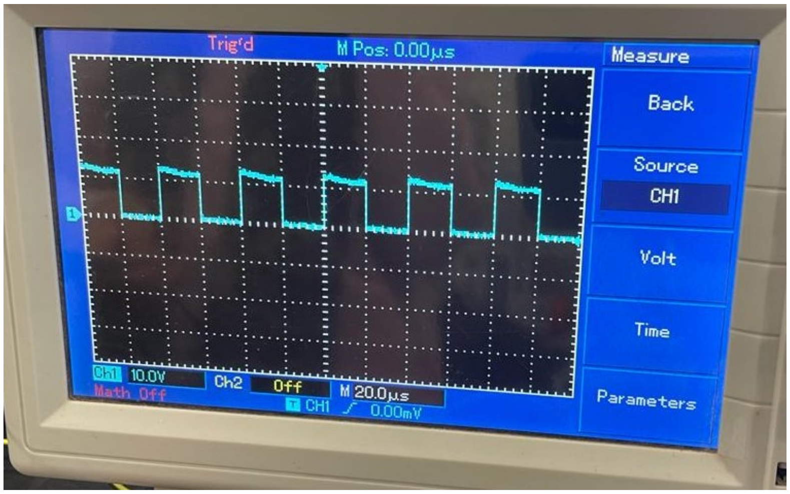
Boosting mode

we have changed the load to be 50 Ω since the converter needed more than 2 A as input and rising the input current to such high value will damage the component

Input voltage = 6 V

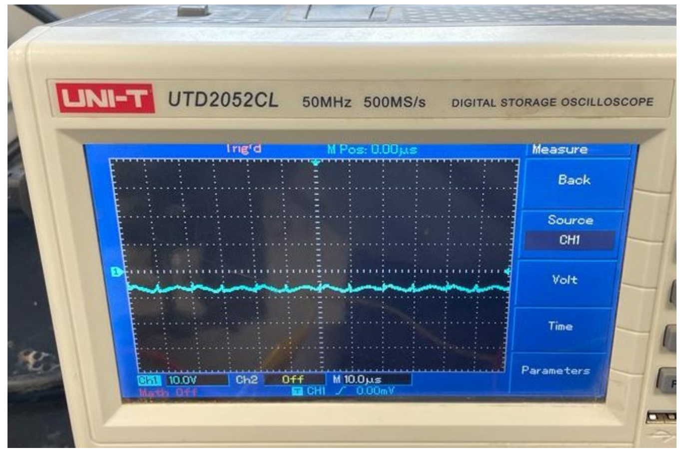
We have reduced the input voltage to reduced the output voltage to keep the resistors and the Breadboard safe.

Duty = 55%

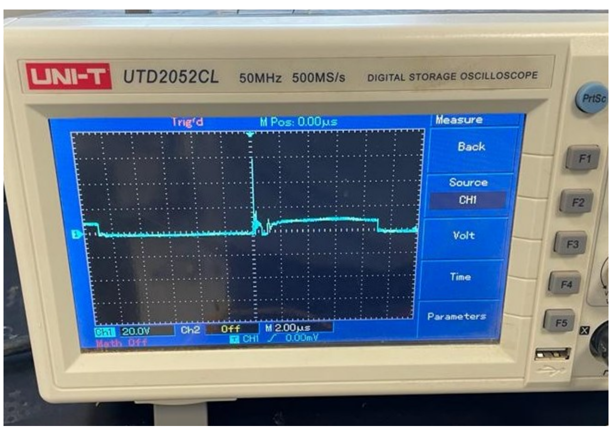


Output voltage

the voltage at the load = 6.65 V, compared to the input which is 6 V, input voltage = 6 V, the Expected output is 7.33 V



MOSFET: Drain to source (the scaling of the oscilloscope is not suitable and needed to be adjusted)



MOSFET: Gate to source