EE463 Static Power Conversion I -Simulation Project III

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5 January 2019

Contents

1 Introduction

In this simulation project, we investigated closed loop speed control of DC motor with using controlled rectifier especially PI control. A brief comparison with other topologies like on-off controller and extended PI controller will introduce first part. At the second part with given specs we design buck converter, simulate it and considering the result we selected components from Digi-Key. Final part of the project, we design boost converter with Webench environment with given specs and our design objectives.

2 Abbreviations

THD	Total Harmonic Distortion
Qx	x'th question
FFT	Fast Fourier Transform
PCC	Point of Common Coupling
l-l	Line to Line
pf	Power Factor
RMS	Root Mean Square

3 Question 1

3.1 3-Phase Thyristor Converter

In this question, we are proposed 3 closed loop control topologies for speed regulation of DC motor with controlled rectifier drive . Characteristics of DC motor we used are followings;

Field Type	Permanent Magnet
Armature Resistance	$R_a = 10\Omega$
Armature Inductance	$L_a = 0.01H$
Back-emf Constant	$0.3\frac{V}{rpm}$
Motor Inertia	$0.4kgm^2$

The proposed methods are

- On/Off Controller
- PI Controller
- Extended PI Controller with linearization

3.1.1 On/Off Controller

The aim of the on/off controller is manipulating firing angle $0°$ and $180°$ depending the error values sign. The main advantages of on/off controller is it is simple, easy to implement and memoryless (no need external memory to store past error values). We drive the controller with 50 Hz. The unit measures to error with 50 Hz sampling frequency and hold it through period. Depending on the error it fires thyristor $0°$ an 180 °. The clear disadvantage of on-off controller is observed when steady-state occur. Since it can not do small changes at error signal, it oscillate around to steady state which called bang-bang.

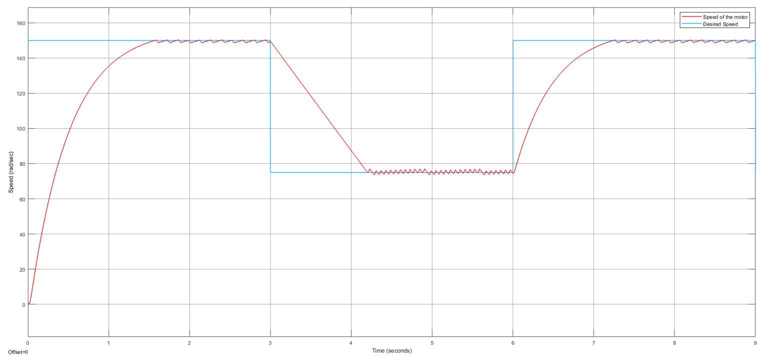


Figure 1: Transient speed response of the motor

This oscillations can be clearly seen by also from controller output.

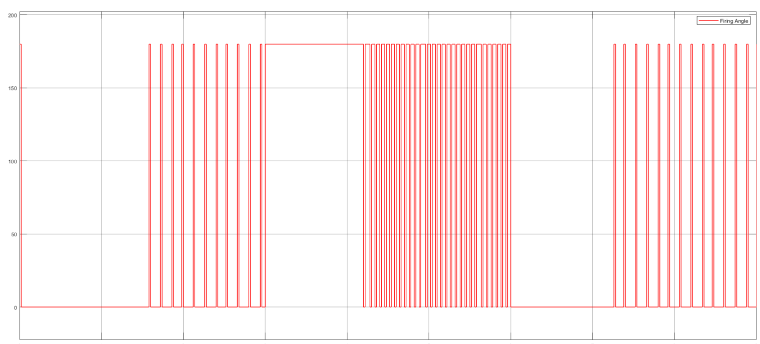


Figure 2: Controller output changes when reference point is changed

3.1.2 PI Controller

PI controller is a closed loop feedback mechanism which mostly used industrial applications. By manipulating the error signal, we can adjust time response of a system. Speed regulation of a DC motor is a type-0 process which has no steady state error when plant driven by PI controller. (since the system type increased). However, the problem is how we closed the feedback loop when we used controlled rectifiers. Since the reference point (speed) and final control element (firing angle) is reversely related we calculate the error signal in following way which is reverse of the what classically done.

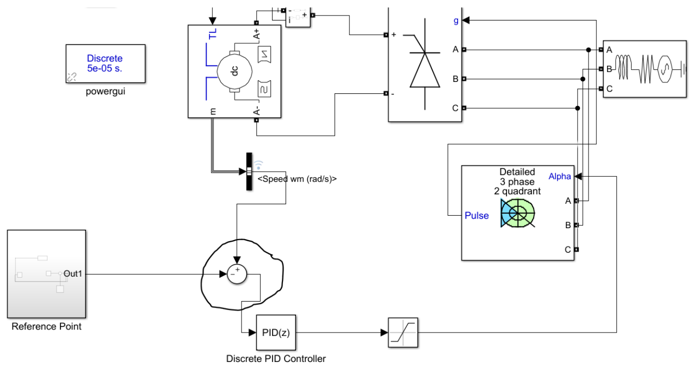


Figure 3: The way that we calculate the error signal

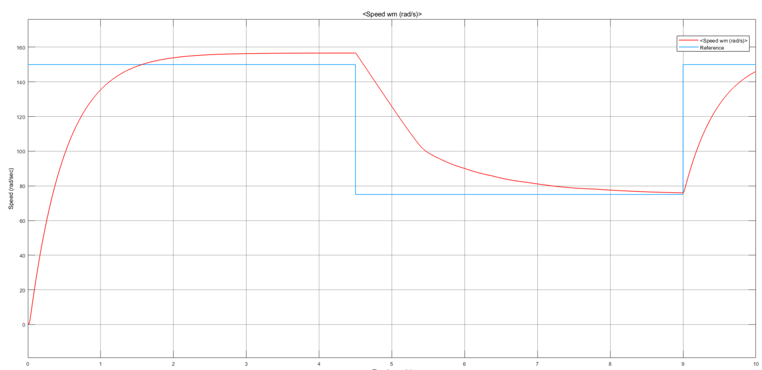


Figure 4: PI controller time response

However, we saw nonzero steady state error which we didn't expect. The reason that why this happened is the speed and firing angle relation is not linear. To overcome this problem we come up with the idea of Extended PI Controller.

3.1.3 Extended PI Controller

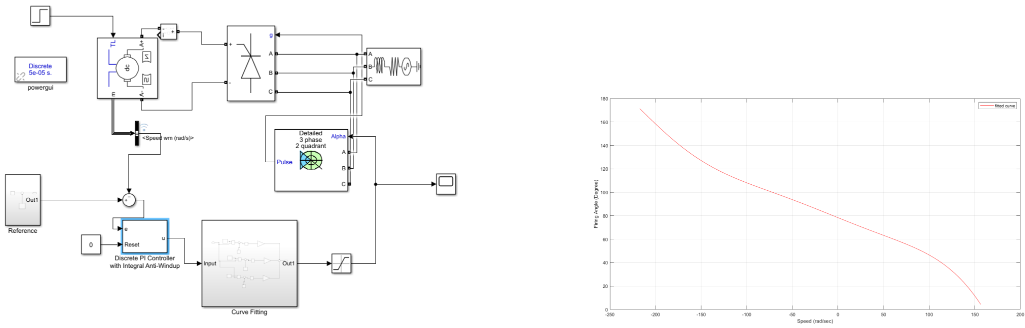
Since the relation between set point (firing angle) and and control variable (speed of the DC motor) is nonlinear, directly obtaining error function between them has some drawbacks. To indicate these drawbacks first, we should identify the our process.

3.1.4 Open loop test

At this part using Simulink, i collect steady state speed data with various firing angles. Then i transfer the data MATLAB environment to fitting a function for it.

3.1.5 Curve Fitting

Using MATLAB Curve Fitting Toolbox, I formulate the speed and firing angle characteristic by using open loop test results. The final function takes speed as a input and converted to required firing angle.



(a) Simulink Model

(b) Speed-firing angle characteristic

Figure 5: Speed firing angle relationship

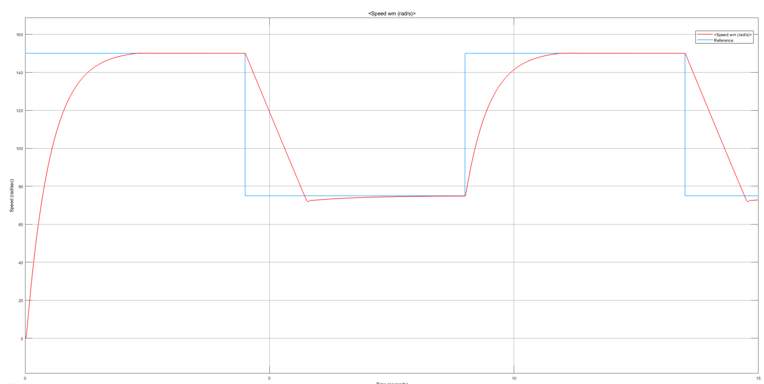


Figure 6: Transient performance of extended PI controller

Overall motivation of such a PI controller is removing the effect of nonlinearities i.e. steady state error. After using this method we significantly improve steady state error performance without sacrifice system speed. Since the fitted function is sum of 3 sines it can be used in micro-controller as a function or look-up table.

Table 1: Pros cons of on-off controller

Pros	**Cons**
It's simple, easy to implement	Steady state oscillation at output (bang-bang)
Fast response	Aggressive change at semiconductor gate can create extra stress at semiconductors
	Since the firing angle changes is extremely high (which can be seen 8) it leads current jumps which lead problems in real life. (considering unexpected inductances at both motor and drive side)

Table 2: Pros cons of PI controller

Pros	**Cons**
Great steady state performance (especially at extended version)	Not simple as on-off controller
Controller has more flexible, designed response can be obtained by re-tuning the controller	Open loop test must be done for controller calculations
	Need hardware (like microcontroller, DSP etc)

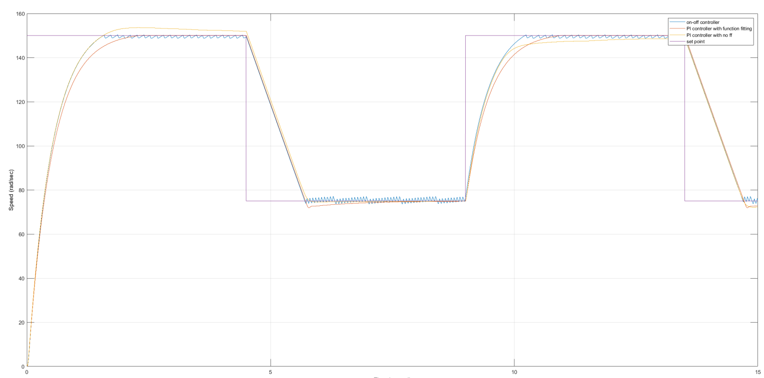
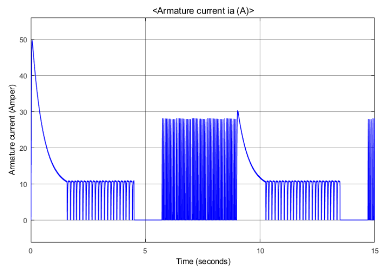
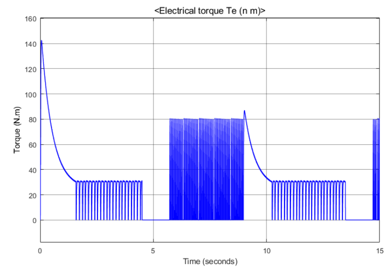


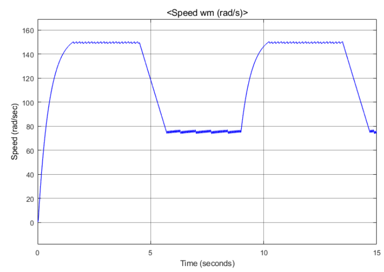
Figure 7: Overall comparison of time responses



(a) Armature current

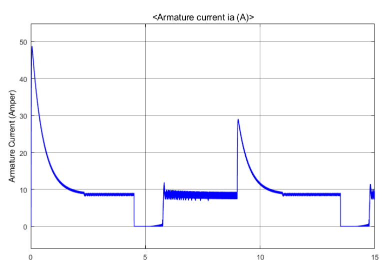


(b) Electrical torque

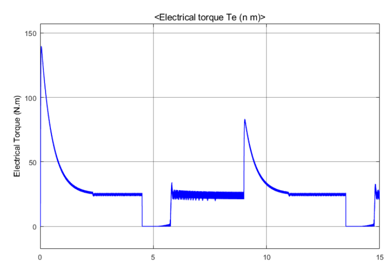


(c) Speed

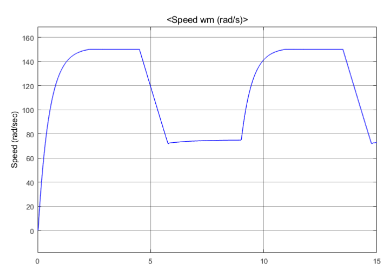
Figure 8: Speed, armature current and electrical torque characteristics of on-off controller



(a) Armature current

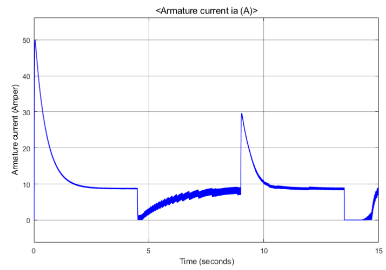


(b) Electrical torque

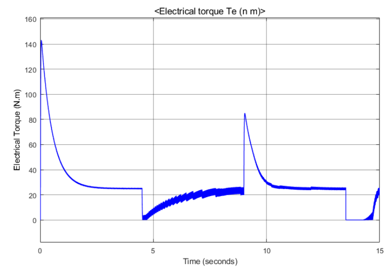


(c) Speed

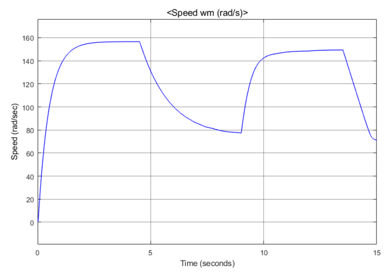
Figure 9: Speed, armature current and electrical torque characteristics of PI controller



(a) Armature current



(b) Electrical torque



(c) Speed

Figure 10: Speed, armature current and electrical torque characteristics of extended PI controller

4 Question 2

Buck converter specs are following,

- $V_{in} = 56\,V$
- $V_{out} = 28\,V$
- $R_{load} = 4\,\Omega$

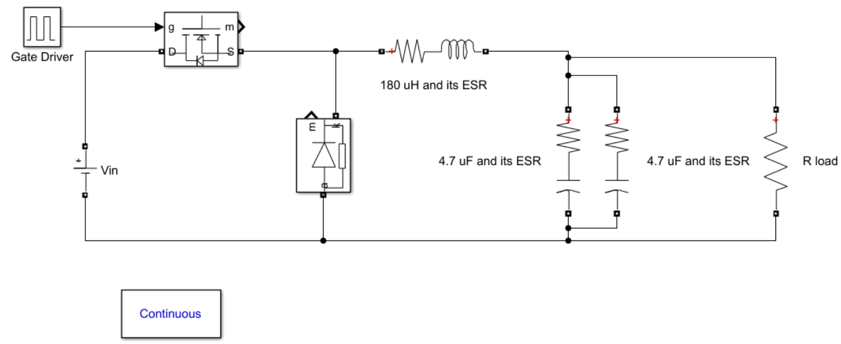


Figure 11: Buck converter topology

We chose 30kHz as a switching frequency for MOSFET. We didn't use secondary MOSFET (synchronous buck converter) since it is low voltage application Schottky diode can be used considering their low loss.

$$D = \frac{V_{out}}{V_{in_{max}}\eta}$$

assuming the overall efficiency around %95, the needed duty cycle

$$D = \%52.6$$

$$\triangle I_L = \frac{(V_{in} - V_{out})D}{f_s L}$$

Choosing $\triangle I_L$ between 0.2 and 0.4 is appropriate relative to [1]. Since we determined all parameters except L, we can compute L.

$$L = 180\mu H$$

Now, we calculated the current rating of the rectifier diode. To reduce losses we used Schottky diode. The forward current rating of the diodes is following [2],

$$I_{Davr} = I_{outmax}(1 - D)$$

$$I_{Davr} = 3.46A$$

The necessary capacitor value can be found like this [3]

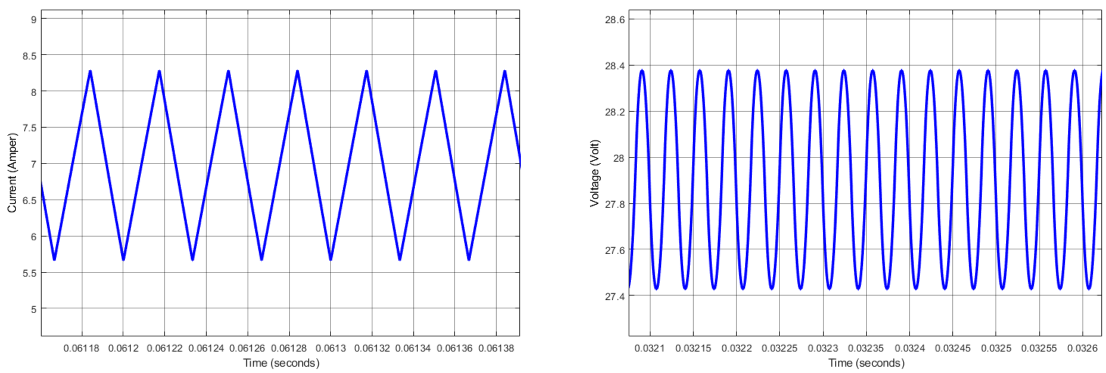
$$C_{out} = \frac{\triangle I_L}{8 f_s \triangle V_{out}}$$

We choose a output voltage which is 28 ± 0.5 V. Therefore, the needed minimum capacitor is $11.1\mu F$. To compensate the ripple caused by ESR of the passive components (since inductor current has ripple every resistor in the current path create ripple). We used slightly larger capacitor.

4.1 Simulation Results

After simulation of the system inferences are;

- DC link capacitor voltage rating must be higher than 40 V
- Inductor has average current rating 7 A with without saturating 10 A current
- Average rectified current of the diode must be greater than x A, reverse voltage rating must be higher than 60 V
- For MOSFET, it can hold 60 V V_{ds} voltages when it off and has 7A average current capability.



(a) Current ripple

(b) Voltage ripple

Figure 12: Ripple Voltage and Current Characteristics

4.2 FET selection

DIODES INCORPORATED

DMT10H015LCG

Maximum Ratings (@T_A = +25 °C, unless otherwise specified.)

Characteristic			Symbol	Value	Unit
Drain-Source Voltage			V_{DSS}	100	V
Gate-Source Voltage			V_{GSS}	±20	V
Continuous Drain Current, V_{GS} = 10V (Note 6)	Steady State	T_A = +25°C T_A = +70°C	I_D	9.4 7.5	A
Continuous Drain Current, V_{GS} = 10V	Steady State	T_C = +25°C T_C = +100°C	I_D	34 21	A
Maximum Continuous Body Diode Forward Current (Note 6)			I_S	1.6	A
Pulsed Drain Current (10µs Pulse, Duty Cycle = 1%)			I_{DM}	54	A
Avalanche Current, L = 3mH (Note 8)			I_{AS}	7.5	A
Avalanche Energy, L = 3mH (Note 8)			E_{AS}	85	mJ

Figure 13: Power loss vs average forward current depending on duty cycle

Product Code	DMT10H015LCG-13-ND
Rated Voltage	100 V
Power Loss	1 $Watt$
Continuous Drain Current	9.4A
Cost	\$ 0.47

4.3 Inductor Selection

Product Code	2300HT-181-H-RC-ND
Average Rating Current	7.2 A
Inductance	180 μH
Type	Toroidal
Cost	\$ 3.59

4.4 Capacitor Selection

Product Code	445-1449-2-ND
Rated Voltage	50 V
Capacitance	6.8 μF
ESR	0.01 Ω

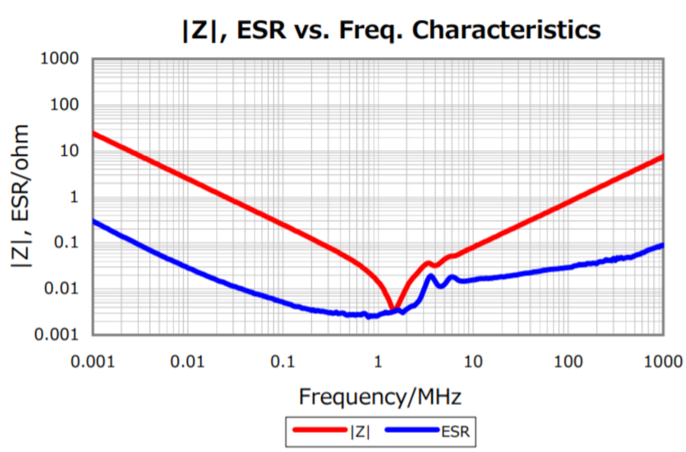


Figure 14: ESR table

4.5 Diode Selection

Product Code	497-8487-1-ND
Average Rectified Current	5 A
Repetitive peak reverse voltage	60 V
Power Loss	2 W
Peak Repetitive Current	15 A
Cost	\$0.91

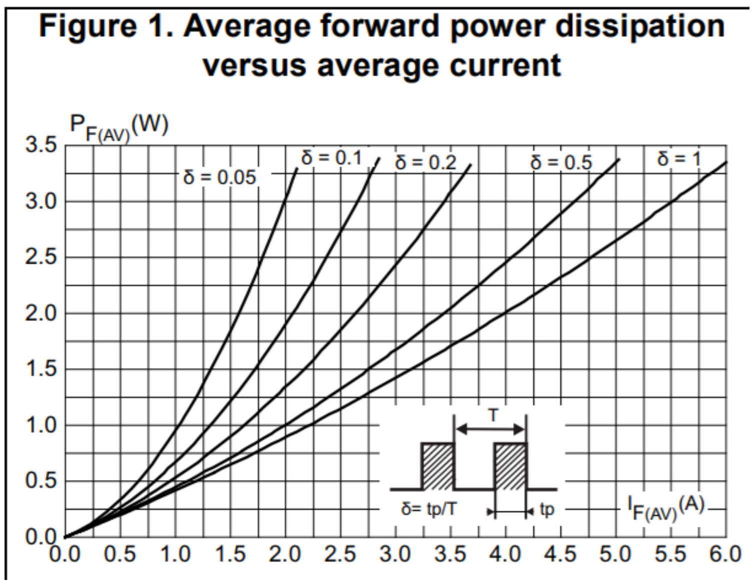


Figure 15: Power loss vs average forward current depending on duty cycle

4.6 Calculating the efficiency

We calculated losses rely on devices datasheets. All devices has their loss vs average current characteristic with various duty cycle.

Diode Power Loss	2 W
MOSFET Power Loss	1 W
ESR Inductor Power Loss	2.76 W
ESR Capacitor Power Loss	0.03 W
Output Power	197.68 W

$$\eta = \frac{P_{out}}{P_{out} + P_{losses}} = \frac{197.68}{197.68 + 5.79} = \%97.15$$

$$Total\ Cost = \$6.23$$

5 Question 3

5.1 Boost Converter Design

Performance requirements and standarts are following,

- $V_{in} = 5 \pm 0.2$
- $P_{out} = 24\,W$, $V_{out} = 12\,V$
- $T_{amb} = 25C^{\circ}$

Then our objectives are,

- Low BOM area
- High efficiency ($> .95$)
- Moderate cost

We selected TPS61088 because it has highest efficiency with 95.8 and low BOM area with 123 mm2 in selection guide. Moreover, its cost is average. BOM cost of it is 3.53$ and IC cost of it is 1.60 $. Circuit schematic of TPS61088 is shown in figure 16 and its charts are shown in figure 17 and 18

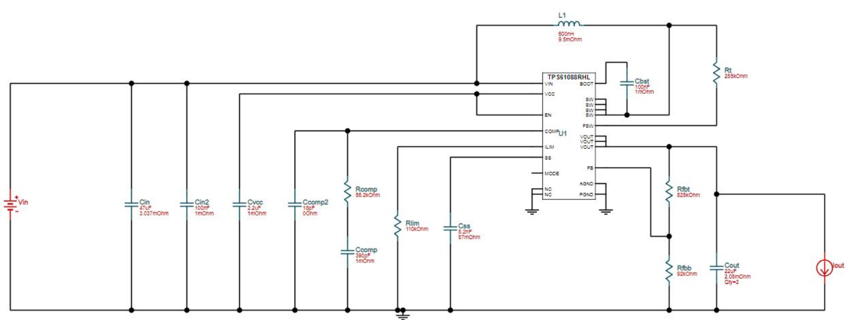


Figure 16: Circuit Schematic of TPS61088 (Boost converter)

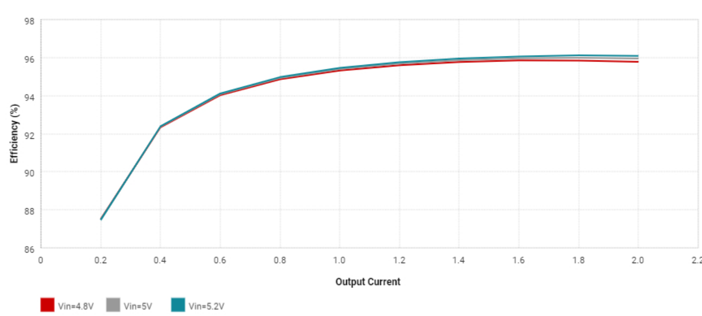


Figure 17: Efficiency vs Output current graph of TPS61088

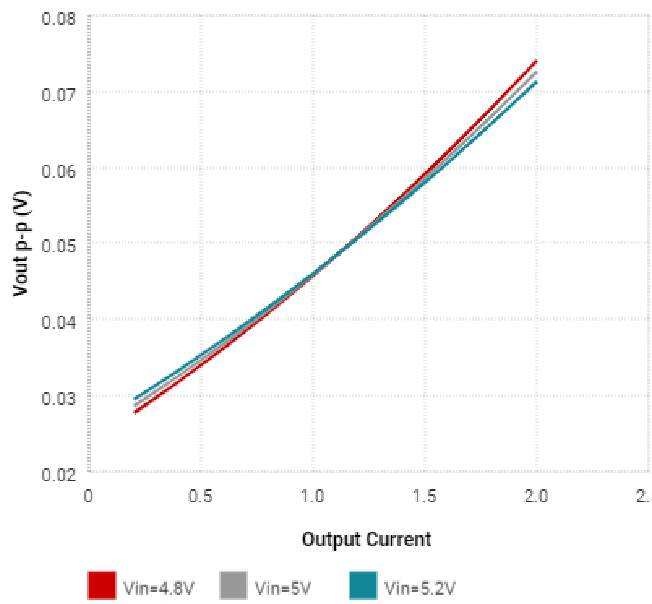


Figure 18: Output voltage ripple vs Output current graph of TPS61088

Table 3: Operation Values of TPS61088

Descriptions	Values
Inductor Current Peak to Peak Value	8.2 A
Output Voltage Peak to Peak Value	74.05 mV
Efficiency	%95.8
IC Junction Temperature	53.33 C
Mode	BOOST CCM
FootPrint	123 mm2
BOM Cost	$3.53

Table 4: Power Dissipation of circuit elements of TPS61088

Circuit Elements	Power Dissipation
Cin	17.04 mW
Cout	8.73 mW
L	301.54 mW
IC	730.06 mW
Total	1.06 W

Our simulation results are shown in figure 19,20 and 21

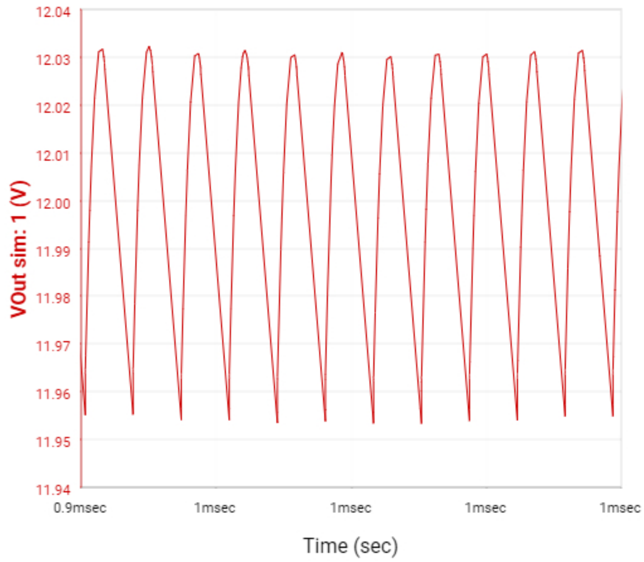


Figure 19: Output Voltage vs Time Graph for Steady-State of TPS61088

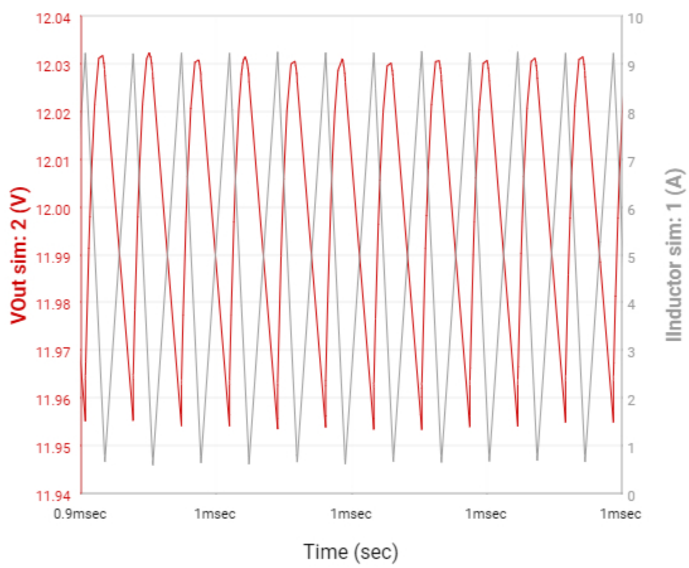


Figure 20: Inductor Current vs Time Graph for Steady-State of TPS61088

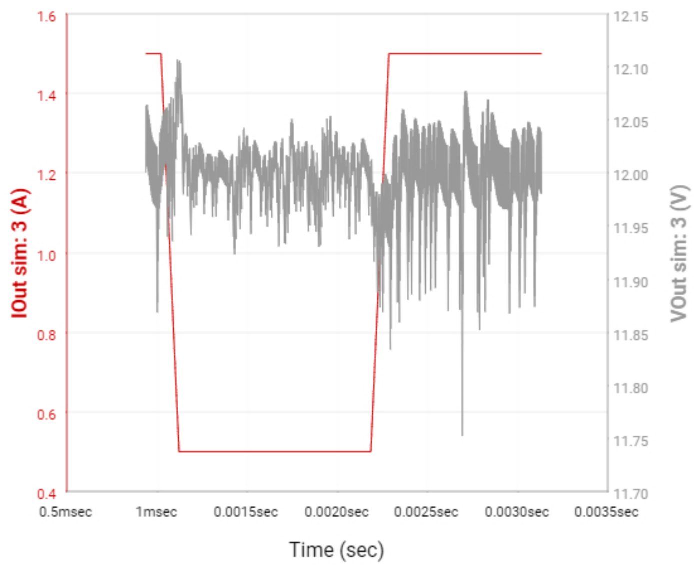


Figure 21: Output Voltage Load Current vs Time for Load Transient of TPS610888

6 Conclusions

In the question 1 we designed three different closed loop control methods of DC motor with controlled rectifier drive. All comparisons and simulation results explained at part 3. In the question 2 we designed a buck converter with given specification. We simulate the circuit for finding component ratings which can be find 4.1. We select the components and compute overall cost and efficiency which stated 4.6. In the question 3 simulation results, the voltage ripple of the device is %0.25. It means that we can assume it is pure DC signal which is desired. Inductor current is charged up to 9 A while output voltage is decreasing. Inductor current is discharging up to 1 A while output voltage is increasing as we expected. In load transient, our output current is pure square wave and changing between 0.5 A and 1.5 A but output voltage has noise. Voltage ripple of output is increased to %2 but it is also acceptable as DC. Therefore, this noise can be neglected. We saw this noise because of scale of graph.

7 References

Basic Calculation of a Buck Converter's Power Stage, TI Application Note

[2] Basic Calculation of a Buck Converter's Power Stage, TI Application Note

[3] Basic Calculation of a Buck Converter's Power Stage, TI Application Note