Electrical Engineering

DC Buck Converter CCM Design

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- Converter Type: DC buck converter
- Input Voltage: 80 V DC
- Output Voltage: 30 V DC
- Power Level: 150 W

II. Initial Design and Simulation

A. Parameters

- Δi_L= current ripple in the inductor
- $\frac{\Delta V_0}{V_0}$ = voltage ripple in the capacitor
- C = capacitor value
- D = duty cycle
- f_s = switching frequency
- I_L = inductor current
- L = inductor value
- P = power level
- R = resistor value
- V_i = input voltage
- V_o = output voltage

B. Theory

To find the duty cycle of this particular buck converter, the equation below is utilized:

$$D = \frac{V_0}{V_i}. \quad (1)$$

Plugging in the given specifications will yield the duty cycle of the system which is important to designing the capacitor and inductor values.

Using the equation:

$$L = V_0 \cdot \frac{(1-D)}{f_s \cdot \Delta i_L} \quad (2)$$

allows for the calculation of the inductor value. The two unknown values in (2) are easy to infer and calculate for. Based on the tests conducted by Texas Instruments on a TPS568230 – high efficiency synchronous buck converter with integrated MOSFETs – a switching frequency between 600 kHz and 1000 kHz will suffice for the buck converter being designed. The chosen switching frequency is then chosen to be 700 kHz [1]. The current ripple in the inductor can be found using the equation:

$$\Delta i_L = \%_{current\ ripple} \cdot I_L. \quad (3)$$

It is good practice to design for a low current ripple which in this case will be no more than 10% of the average inductor current. Next is finding the inductor current by utilizing the two equations:

$$R = \frac{(V_0)^2}{P} \quad (4)$$

and

$$I_L = \frac{V_0}{(1-D) \cdot \mathrm{R}}. \quad (5)$$

Equation (4) is simply Ohm's law considering the given specifications. Plugging in the resistor value in (5) gives the inductor current which will finally allow the calculation for the current ripple in the inductor in (3). Going back to (2) with all these algebra and inferences finally gives a final inductor value.

A similar process is done to design the capacitor for the buck converter with the equation:

$$C = \frac{(1-D)}{8 \cdot L \cdot {f_s}^2 \cdot \frac{\Delta V_0}{V_0}}. \quad (6)$$

The voltage ripple in the capacitor will not exceed 1% of the average output voltage. The final step is to plug all the calculated and known variables into (6) to find the final capacitor value.

C. Initial Design

TABLE I

IDEAL CALCULATED COMPONENT VALUES

Components	Value
Duty Cycle	.375
Switching Frequency	700 kHz
Resistor	6 Ω
Inductor Current	8 A
Inductor Current Ripple	.8
Inductor	33.482 µH
Capacitor Voltage Ripple	.01
Capacitor	476 nF

Because TABLE I shows ideal component values, finding the closest available resistor, inductor, and capacitor values in the market is good measure to simulate a buck converter that behaves similarly to real life.

TABLE II

REAL WORLD RESISTOR, INDUCTOR, AND CAPACITOR VALUES USED INSTEAD

Components	Value
Resistor	6 Ω
Inductor	33.33 µH
Capacitor	.47 µF

NOTE: The component values listed are available for purchase on Mouser Electronics.

Next is determining which diode and NMOS to utilize. The models of these components are chosen in LTSpice based on a set of criteria.

The diode needs to meet the criteria:

- High breakdown voltage (greater than the input voltage)
- Low ohmic resistance

The MOSFET needs to meet the criteria:

- High drain-to-source voltage (equal to or greater than the input voltage)
- Low ON resistance

TABLE III

REAL WORLD DIODE AND MOSFET CHOSEN

Components	Model	Characteristics
Schottky Diode	MBRS1100	V_{brkdn} = 100 V R_s = .0079 Ω
MOSFET	IPT020N10N3	V_{DS} = 100 V R_{ON} = .0017 Ω

NOTE: The manufacturers of the Schottky diode and the MOSFET are OnSemi and Infineon respectively.

The last step is determining the parameters of the pulse wave being inputted to the gate of the MOSFET. Initially, the MOSFET should be supplied 0 V and turned on at 10 V. Regarding the period, there should be no delay along with minimal rise and fall time of about 1 ns. Next, the on-time should be the product of the duty cycle and the inverse of the duty cycle. Finally, the period of the pulse wave should be the inverse of the duty cycle.

D. Model and Results

The following model and simulations of the buck converter are completed using LTSpice.

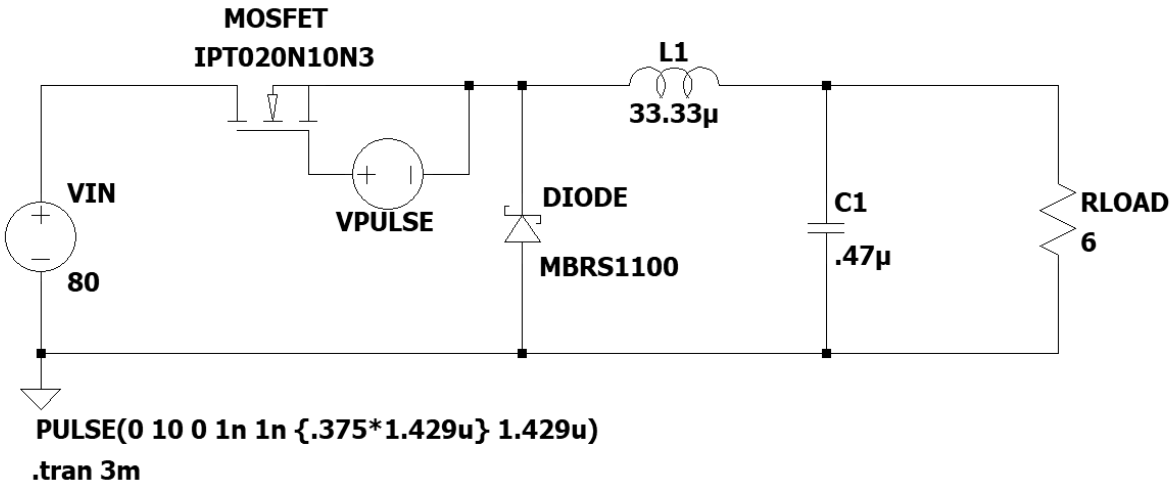

Fig. 1. Initial design of the buck converter with a transient run time.

Rather than using an ideal PWM to drive the MOSFET, a Pulse-Width-Modulation (PWM) controller and a high voltage high side gate driver are utilized to take the buck converter design to the next level.

The model of the PWM chip and the gate driver used are the LTC6992 and the LTC4446 respectively – both manufactured by Analog Devices – due to their simplicity. Many of the specifications for concepts such as the voltage common collector, the type of diode needed, capacitor value, and other pin layouts can be found on their data sheet.

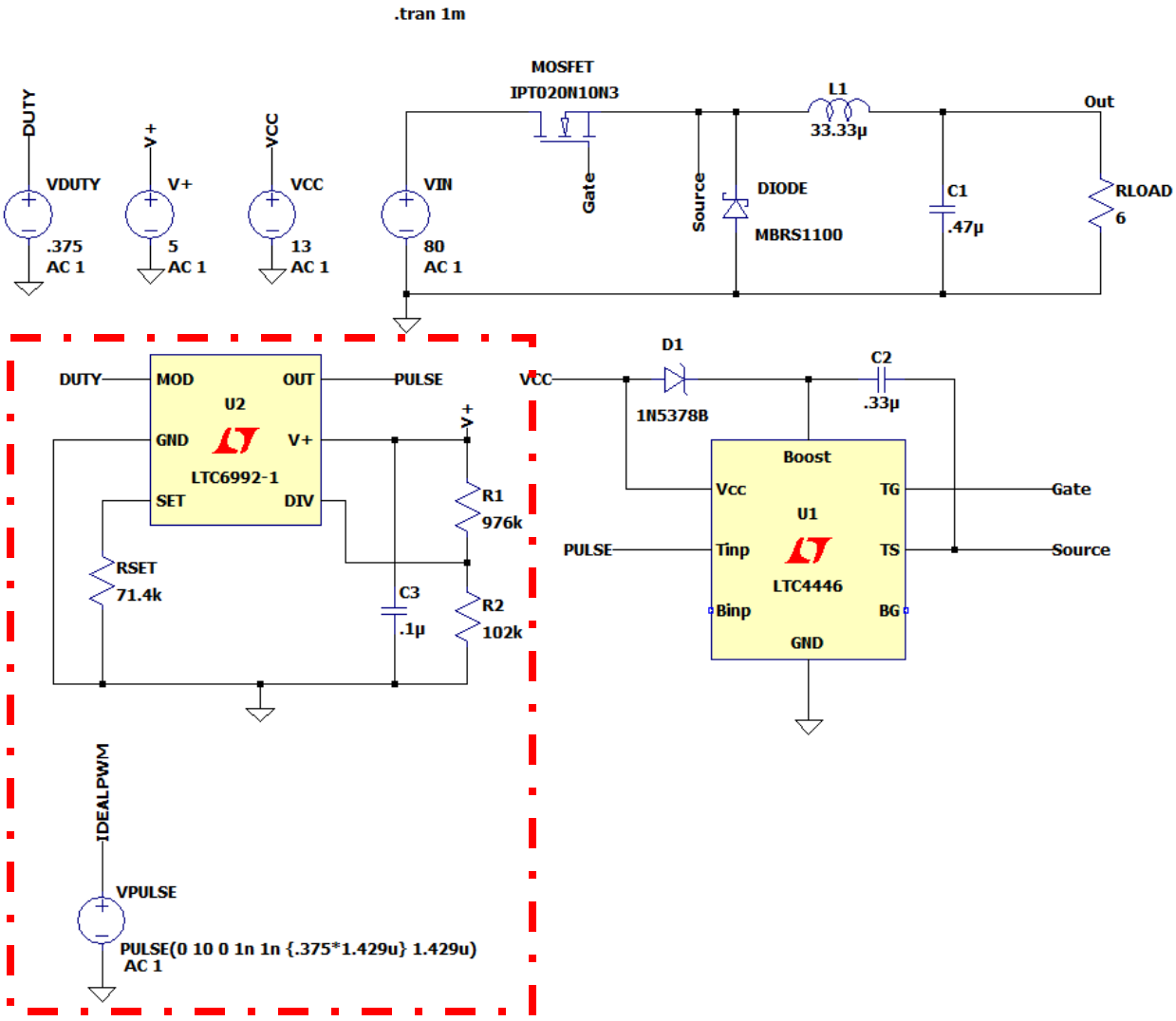

Fig. 2. Buck converter with a PWM controller and a high voltage high side gate driver.

With the model of the buck converter in Fig. 2 now available, it is important to verify it by examining the output voltage, inductor current and current ripple, and the load resistor and diode current. As a side note, the ideal PWM signal and the PWM controller are in the dashed box to show that they can represented both ways. For the purpose of this project, the PWM controller is used to simulate a buck converter that is as close to the real world.

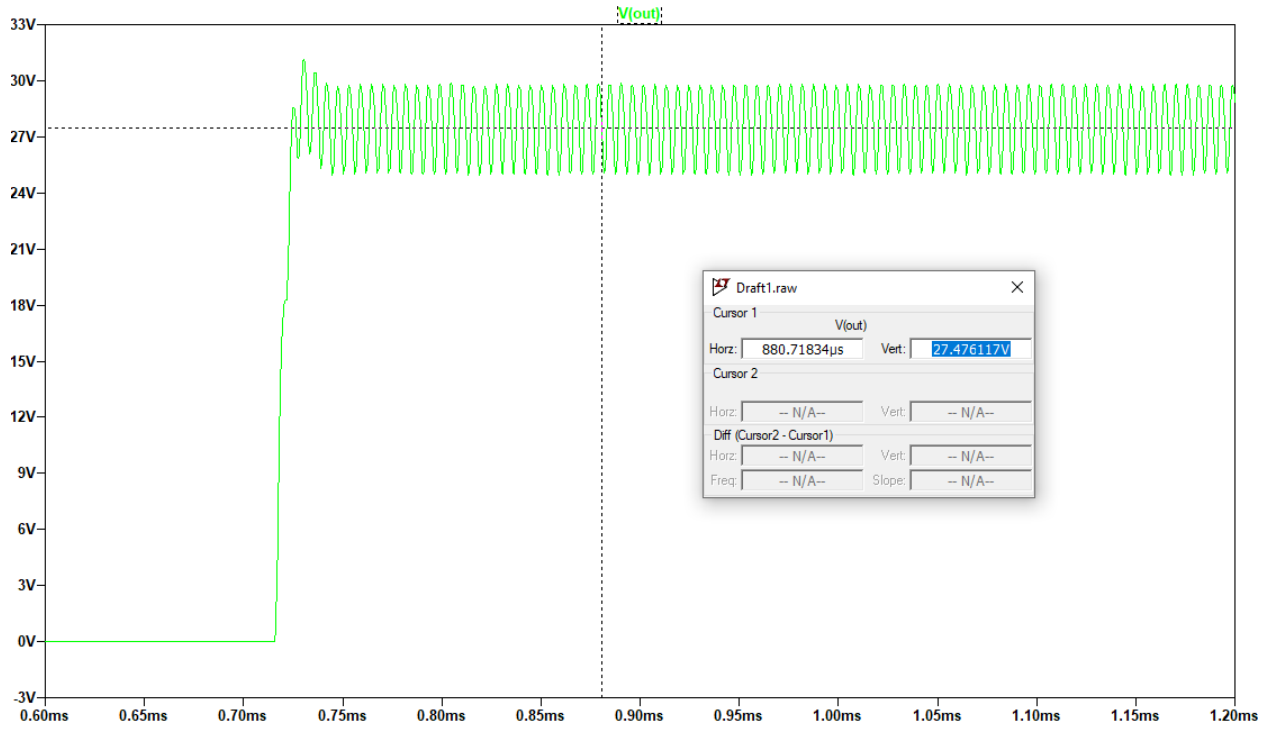

Fig. 3. Output voltage of the buck converter with the gate driver shown in Fig. 2.

Using the cursor in LTSpice show that the output voltage oscillates within 27.48 V which is relatively close to the specified design output voltage of 30 V.

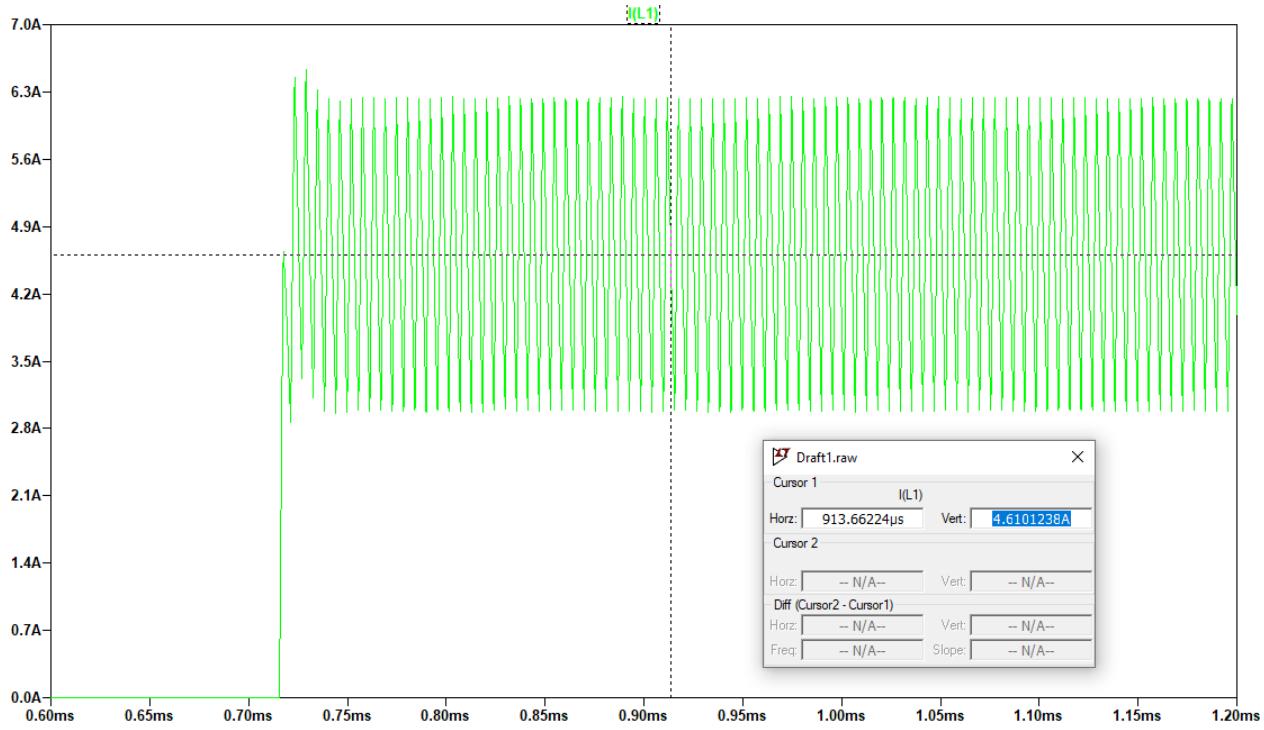

Fig. 4. Inductor current of the buck converter with the gate driver shown in Fig. 2.

Based on Fig. 4, the simulated inductor current seems to be lower than the measured inductor current of 8 A. The LTSpice cursor show that the inductor current saturates at about 4.61 A which seems fine since the design of the buck converter was meant to simulate close to a real one with the rounding of components and having extra components such as the PWM controller and the gate driver.

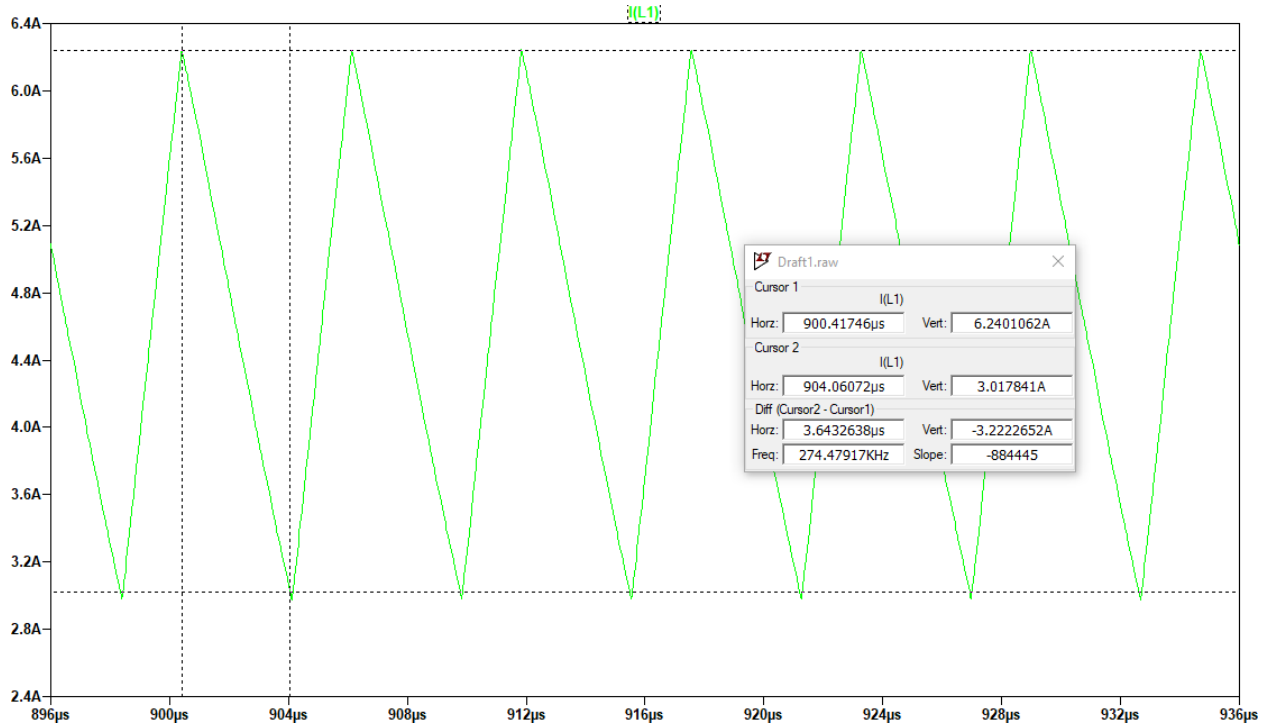

Fig. 5. Zoomed in figure of Fig. 4 with cursors to help calculate the current ripple within the inductor.

With basic algebra, the inductor current ripple is simulated to be 3.22 which is about 70% of the simulated current and larger than .8 as calculated in TABLE I. This is due to the high input voltage being proportional to the higher ripple current for a fixed inductor. A low ESR at the input may help fix this problem after designing a compensator for the buck converter.

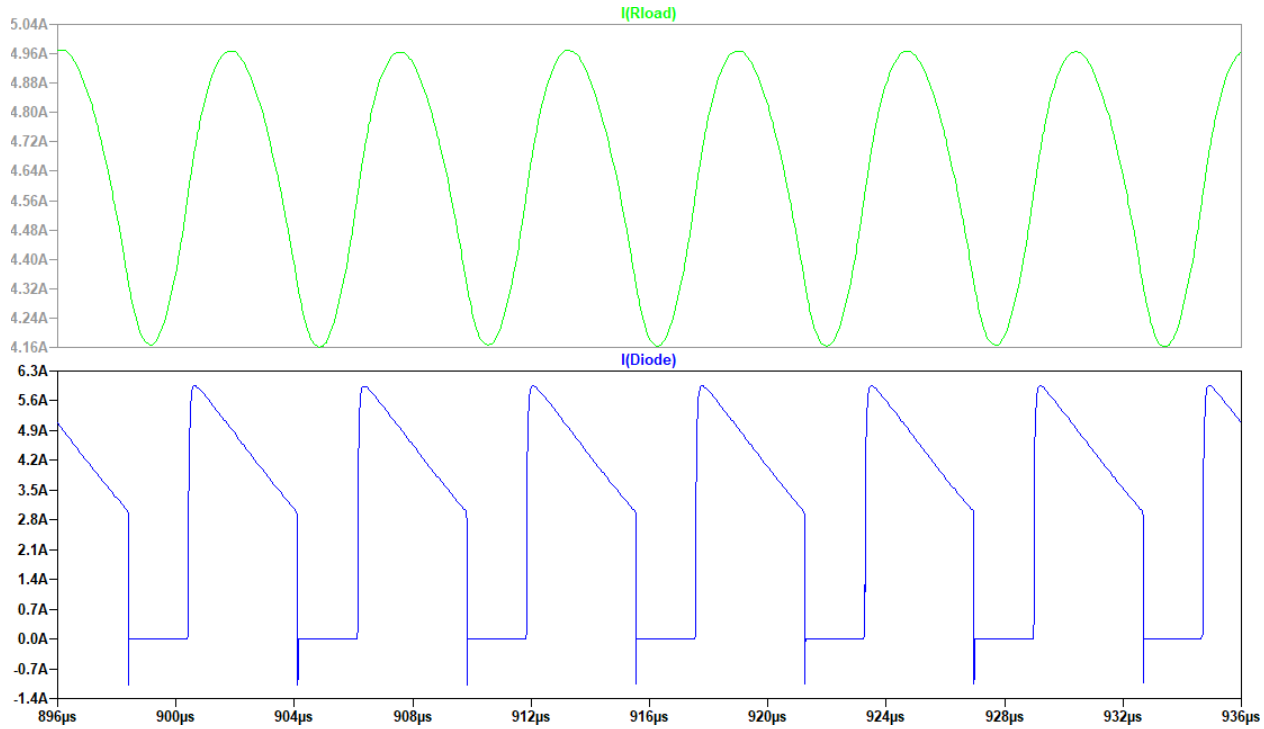

Fig. 6. Current passing through the load resistor and the Schottky diode of the buck converter with the gate driver shown in Fig. 2.

The results from Fig. 6 confirm that the instantaneous current passing through the buck converter is approximately around 4 A as in Fig. 4. Furthermore, it suggests that the load resistor and the diode are working as intended despite the current ripple observed in Fig. 5.

III. Compensator Design

A. Theory

The purpose of adding a compensator to the buck converter is to counteract some of the gains and phases contained in the system that could harm the stability of the power supply. Furthermore, adding a compensator allows the closed loop system to satisfy the stability criteria.

A Type III compensator will be designed for the buck converter designed in the previous section. This compensator has two poles and two zeroes which have to be designed for by finding the ESR and LC resonant frequency of the system. This is done by removing any non-linear components of the system and running AC analysis on the system.

B. Design

The first step to designing the compensator is by removing any non-linear components of the buck converter.

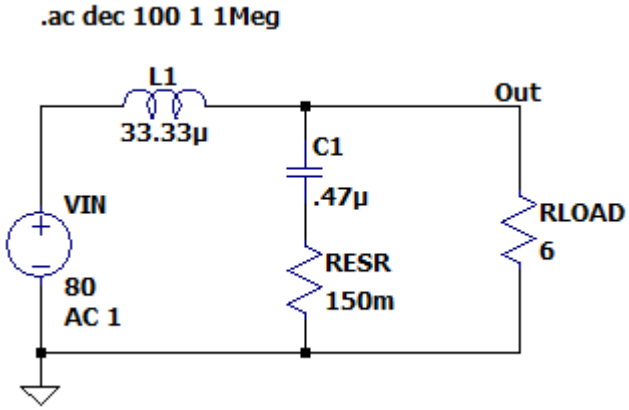

Fig. 7. Linearized model of the buck converter showed in the previous section.

As seen in Fig. 7, the capacitor ESR is chosen to be the typical 150 mΩ.

The ESR zero frequency is calculated using the equation:

$$f_{ESR} = \frac{1}{2 \cdot \pi \cdot R_{ESR} \cdot C_1}. \quad (7)$$

Similarly, the LC resonant frequency can be calculated using:

$$f_{LC} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_1 \cdot C_1}} . \quad (8)$$

Fig. 8. Figure of a Type III compensator from Texas Instruments' informational guide. Adapted from [1].

The operational amplifier configuration's resistors and capacitors can be designed via the frequencies. The equations needed to design such components, and the frequencies of the pole and zeroes are:

$$f_0 = f_{LC}, \quad (9)$$

$$f_{z1} = f_{z2} > f_{LC}, \quad (10)$$

$$C_2 = \frac{1}{2 \cdot \pi \cdot R_1 \cdot f_{z1}} \text{ ; where } R_1 \text{ will be set as 1 M}\Omega, \quad (11)$$

$$f_{p1} = f_{p2} \cong f_{ESR}, \quad (12)$$

$$R_3 = \frac{1}{2 \cdot \pi \cdot C_2 \cdot f_{p2}} , \quad (13)$$

$$C_3 = \frac{1}{2 \cdot \pi \cdot R_2 \cdot f_{p2}} \text{ ; where } R_2 \text{ will be set as 10 M}\Omega, \quad (14)$$

and

$$C_1 = \frac{1}{2 \cdot \pi \cdot R_2 \cdot f_{z2}}. \quad (15)$$

With all of these equations, only the simple algebra is left to finish designing the Type III compensator before modelling it on LTSpice.

Table IV

TYPE III COMPENSATOR DESIGN VALUES

Elements	Value
ESR Frequency (f_{ESR})	2.26 MHz
LC Resonant Frequency (f_{LC})	40.21 kHz
f_0	40.21 kHz

$f_{z1} = f_{z2}$	41 kHz
$f_{p1} = f_{p2}$	2.28 MHz
R_1	1 MΩ
R_2	10 MΩ
R_3	18 kΩ
C_1	.38 pF
C_2	3.88 pF
C_3	.01 pF

NOTE: The resistor and capacitor values are rounded to the closest available values on Mouser Electronics.

The next step is to model the compensator and simulate it on LTSpice. The closed loop gain of the compensator must be verified by itself since the buck converter has many non-linear components.

C. Model and Results

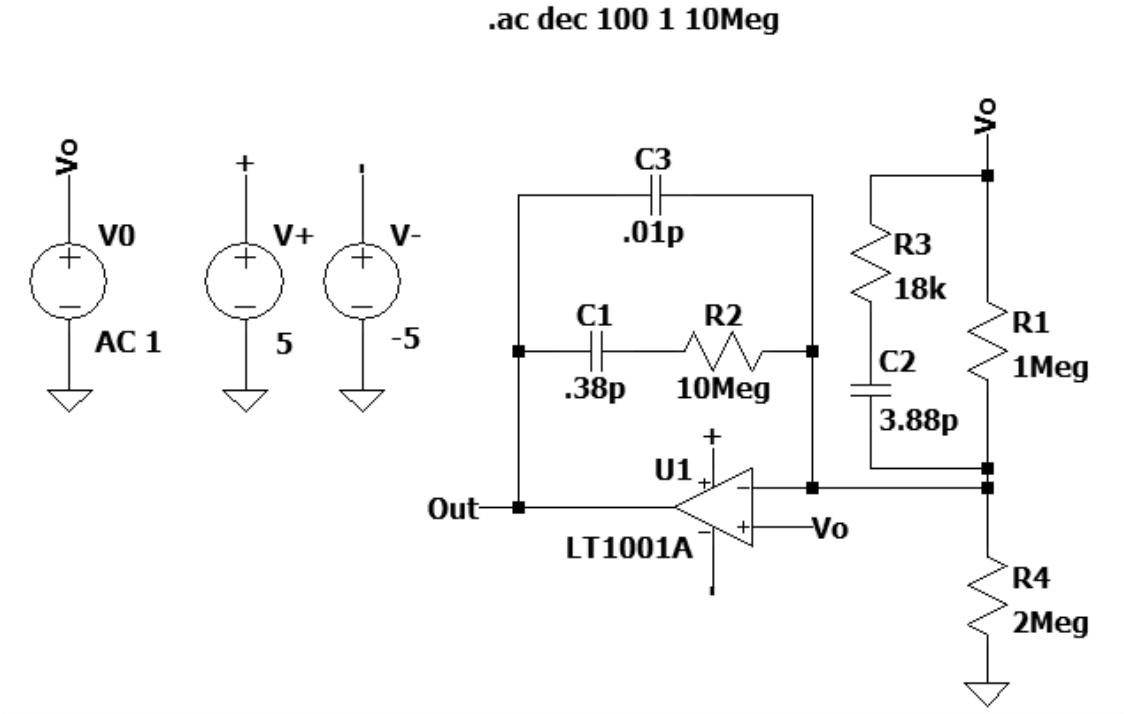

Fig. 9. Closed loop gain of the compensator based on the design values from Table 4.

The final step is to analyze if the compensator is stable via a Bode plot and observing the margins.

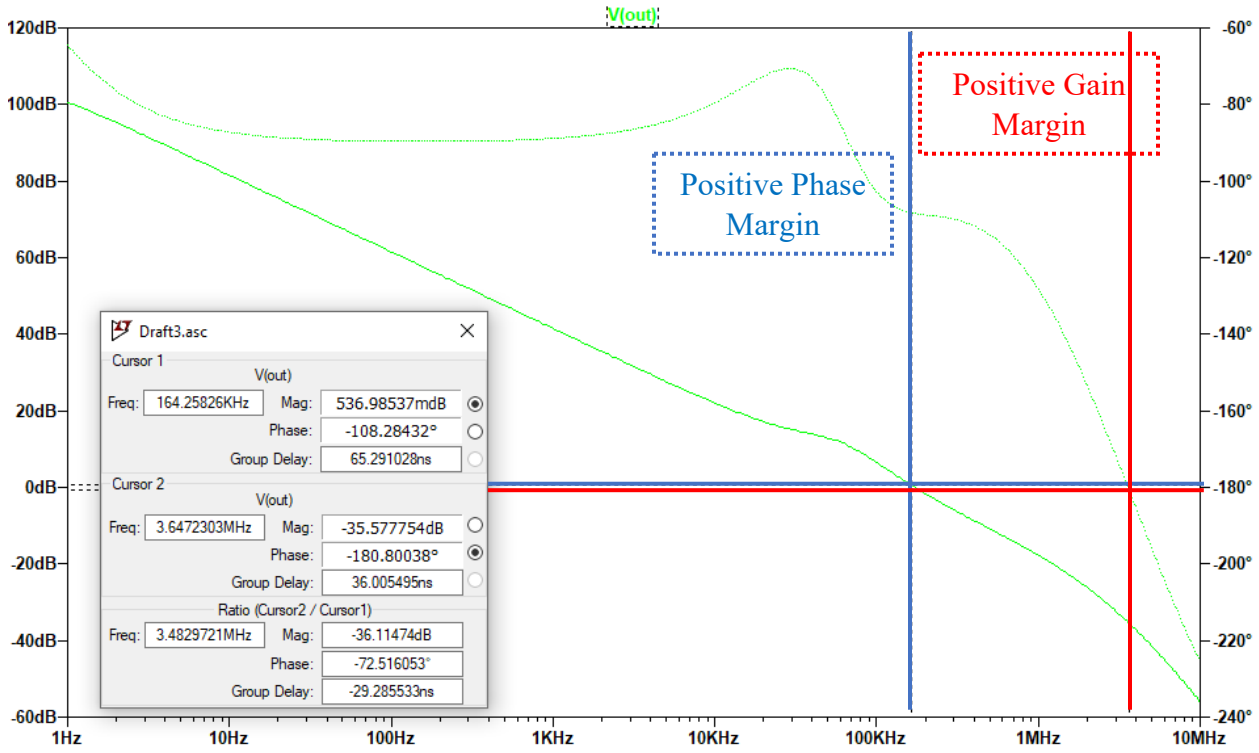

Fig. 10. Bode plot of the compensator design shown in Fig. 9 including its gain (dB) and phase (°) with margins.

Around 0 dB or 164.26 kHz, the phase is -108.28° which is below -180° hence suggesting a positive phase margin. Similarly, at -180° the gain is below zero at 3.65 MHz, therefore suggesting a positive gain margin. With both the gain and the phase being positive, the compensator is stable and works as intended.

IV. Final Design

The fully designed DC-DC buck converter CCM schematic with all the stages connected to each other to form a closed loop system is shown below.

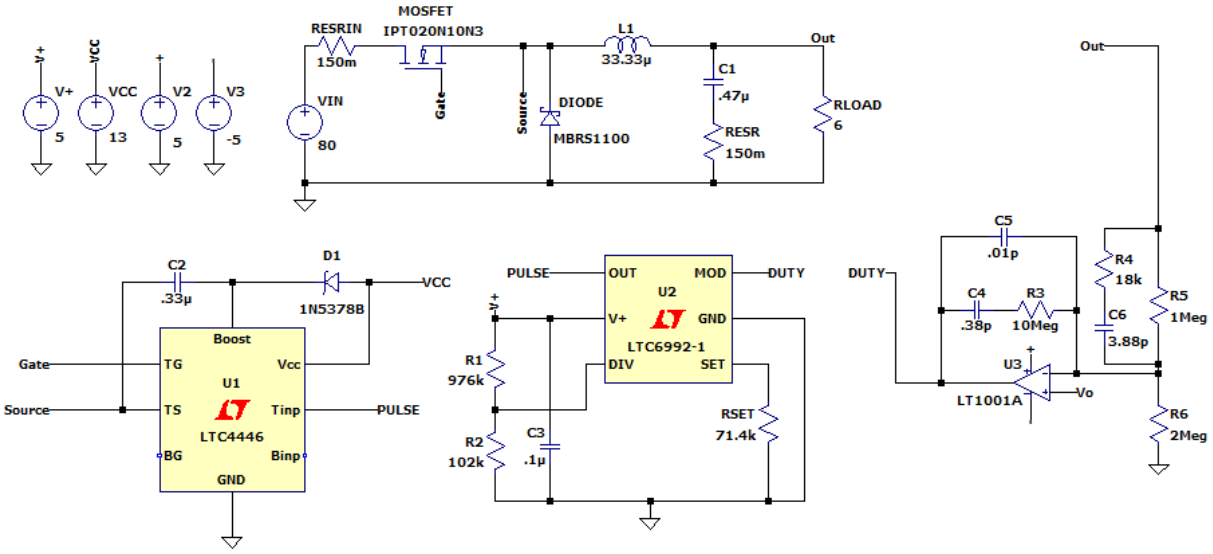

Fig. 11. Final schematic of the buck converter connected to the Type III compensator, PWM controller, and gate driver.

V. Bill of Materials

Label	Part Model	Value/Type	Qty.	Vendor	Unit Price
Capacitors					
C1	C0402C474K8RACTU	.47 µF	1	Mouser	$0.54
C2	HMK316B7334MLHT	.33 µF	1	Mouser	$0.46
C3	C1206C104K3GACAUTO	.1 µF	1	Mouser	$2.01
C4	04025JR38PBSTR	.38 pF	1	Mouser	$0.23
C5	GRM31CD80G107MEA8L	.01 pF	1	Mouser	$0.76
C6	GJM0335G2A3R8WB01D	3.8 pF	1	Mouser	$0.41
Diodes					
DIODE	MBRS1100T3G	Schottky	1	Mouser	$0.52
D1	1N5378B	Zener	1	Newark	$0.44
IC Chips					
MOSFET	IPT020N10N3	NMOS	1	Mouser	$8.42
U1	LTC4446IMS8E#PBF	Driver	1	Mouser	$4.83
U2	LTC6992IS6-3#TRMPBF	PWM	1	Mouser	$4.89
U3	LT1001ACN8#PBF	OpAmp	1	Mouser	$7.80
Inductors					
L1	TCK-075	33.33 µH	1	Mouser	$7.04
Resistor					
RESR	SMW7R15JT	150 mΩ	1	Mouser	$4.08
RESRIN	SMW7R15JT	150 mΩ	1	Mouser	$4.08
RLOAD	WSC00026R000FEB	6 Ω	1	Mouser	$1.19
RSET	ERJ-U02D7152X	71.4 kΩ	1	Mouser	$0.16
R1	CR0603-FX-9763ELF	976 kΩ	1	Mouser	$0.10
R2	RP73PF1E102KBTDF	102 kΩ	1	Mouser	$0.62
R3	RCV251210M0JNEGAT	10 MΩ	1	Mouser	$1.16
R4	MCS04020D1802BE000	18 kΩ	1	Mouser	$0.46
R5	RCV25121M00FKEGAT	1 MΩ	1	Mouser	$1.16
R6	RCV25122M00FKEGAT	2 MΩ	1	Mouser	$1.16

VI. References

[1] E. Guo and H. Xie. *How the Switching Frequency Affects the Performance of a Buck Converter*.(2019).[Online]. Available: https://www.ti.com/lit/an/slvaed3/slvaed3.pdf

[2] Sunpower Electronics. “Equivalent Series Resistance (ESR)”. sunpower-uk.com. https://www.sunpower-uk.com/glossary/what-is-equivalent-series-resistance-esr/ (accessed July 20, 2021).

[3] Stack Exchange. “Equivalent Series Resistance (ESR)”. electronics.stackexchange.com. https://electronics.stackexchange.com/questions/224678/loop-compensation-design-of-buck-converter (accessed July 22, 2021).