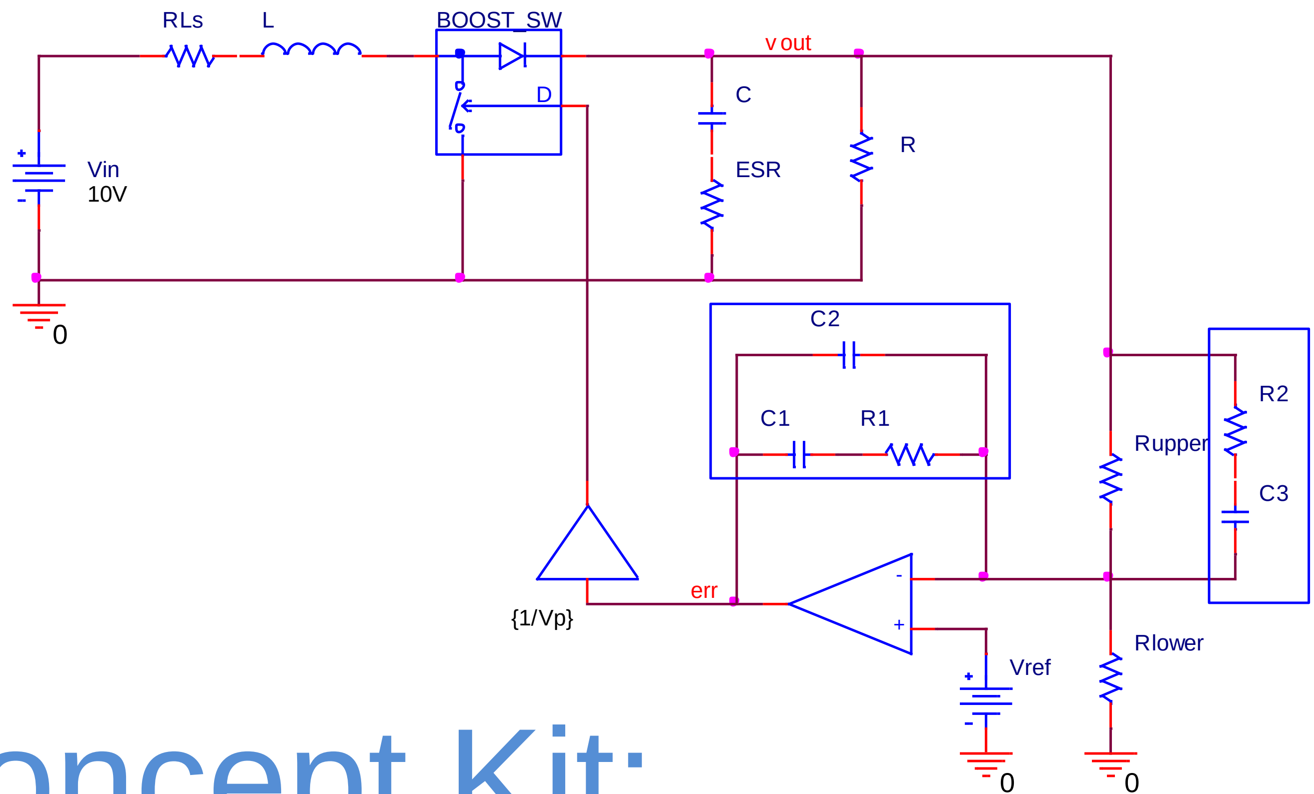


Concept Kit:

PWM Boost Converter Average Model

Contents

- The PWM Boost Converter Topology (Voltage Mode)
  - Averaged Boost Switch Model
- Boost Converter Design Workflow
  - Design Specification (Example)
    1. Setting PWM Controller's Parameters.
    2. Programming Output Voltage: Rupper, Rlower
    3. Inductor Selection: L, R_{LS}
    4. Capacitor Selection: C, ESR
    5. Stabilizing the Converter (Example)
- Load Transient Response Simulation (Example)

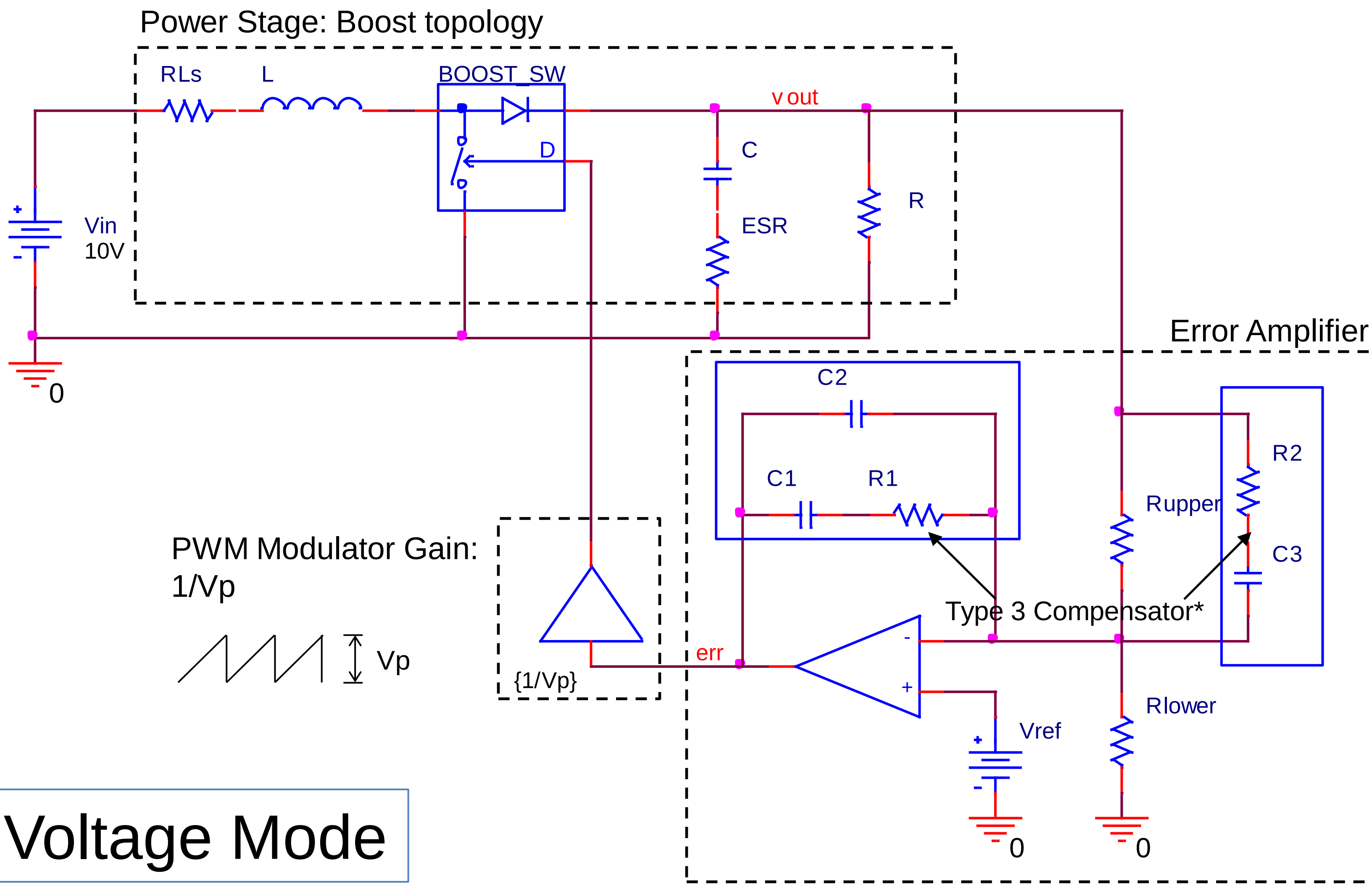
<u>Appendix</u>

A. Boost Converter Calculator (Excel sheet)

B. Feedback Loop Compensators

C. Simulation Index

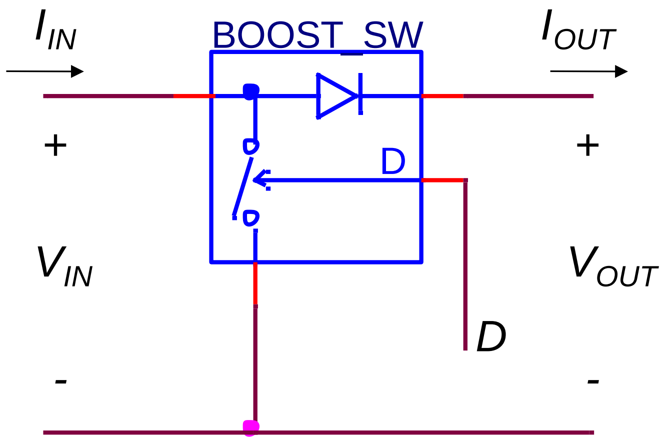
The PWM Boost Converter Topology



Voltage Mode

* Please see appendix B for the detail

Averaged Boost Switch Model



- The Averaged Boost Switch Model represents relation between input and output of the switch that is controlled by duty cycle – d (value between 0 and 1).

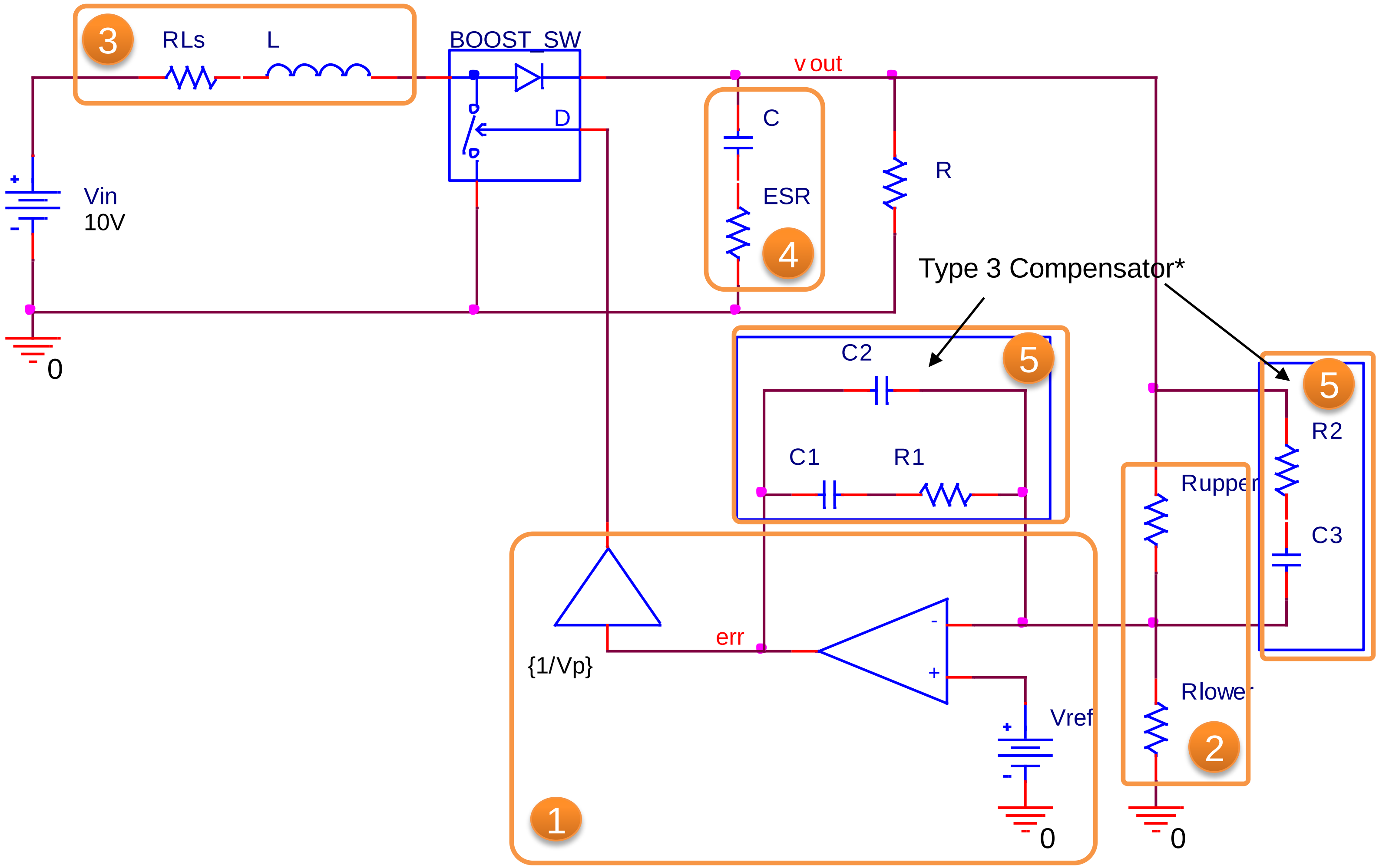
- Transfer function of the model is $$V_{OUT} = \frac{V_{IN}}{(1-D)} \qquad (1)$$

- The current flow into the switch is $$I_{IN} = \frac{I_{OUT}}{(1-D)} \qquad (2)$$

Boost Converter Design Workflow

1. Setting PWM Controller's Parameters: **VREF, VP**
2. Setting Output Voltage: **Rupper, Rlower**
3. Inductor Selection: **L, R_{Ls}**
4. Capacitor Selection: **C, ESR**
5. Stabilizing the Converter: Type 3 Compensator: **R1, R2, C1, C2, and C3**
   - ***Step1*: Open the loop** *with LoL=1kH and CoL=1kF then inject an AC signal to generate Bode plot.*
   - ***Step2*: Run the AC sweep** *without compensator.*
   - ***Step3*: Select a crossover frequency, f_c,** *select the value a little lower than the suggested value.*
   - ***Step4*: Read the Gain value (dB) at the f_c** *from the Bode plot, Then put the values to the sheet.*
   - ***Step5*: R C values are suggested,** *input the values to the elements of the compensator.*
6. Load Transient Response Simulation

Buck Regulator Design Workflow



* Please see appendix B for the detail

Design Specification (Example)

A boost converter is designed to deliver 12V, 1.5A from a 3.3 V battery

<u>Step-Up (Boost) Converter</u> :

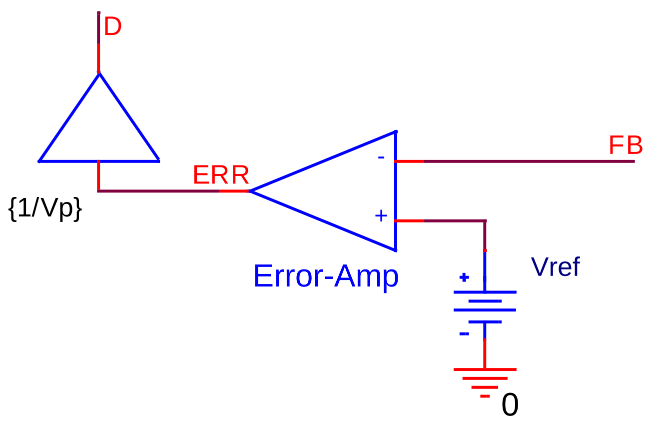
$$\left.\begin{array}{l} \bullet\ V_{in,max} = 3.63\ (V) \\ \bullet\ V_{in,min} = 2.97\ (V) \end{array}\right\} V_{in} = 3.3 \pm 10\%$$

- V_{out} = 12 (V)
- $V_{out,\ ripple}$ = 180m$V_{P\text{-}P}$ *(1.2%)*
- $I_{o,max}$ = 1.5 (A)
- $I_{o,min}$ = 0.2 (A)

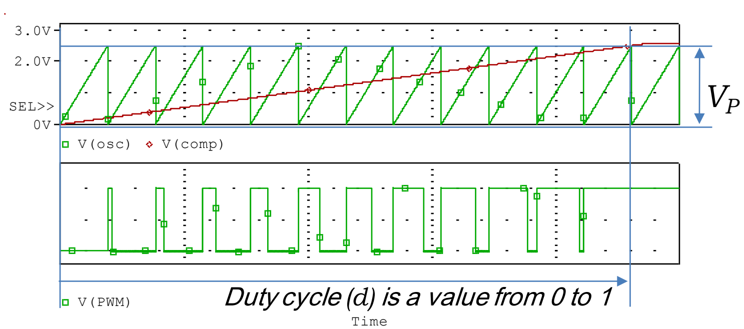
<u>Control IC</u> :

- Part # TPS43000 (PWM Controller IC)
- Switching Frequency – fosc = 300 (kHz)

1 Setting PWM Controller's Parameters



The Error-Amp. is used to transfer the error voltage (between FB and V_{REF}) to be the duty cycle.



- **VREF**, feedback reference voltage, value is given by the datasheet
- **VP = ** the sawtooth peak voltage.
  - If V_P does not provided, it could be calculated from:

$$VP = \Delta V_{FB} / \Delta d \qquad (3)$$

$$\Delta V_{FB} = V_{FBH} - v_{FBL}$$

$$\Delta d = d_{MAX} - d_{MIN}$$

where

v_{FBH} is maximum FB voltage where d = 0

v_{FBL} is minimum FB voltage where d =1(100%)

d_{MAX} is maximum duty cycle, e.g. d = 0(0%)

d_{MIN} is minimum duty cycle, e.g. d =1(100%)

- f_{osc} = Modulation frequency or switching frequency .

※ If v_{FBH} and v_{FBL} are not provided, the default value, VP=2 could be used.

1 Setting PWM Controller's Parameters (Example)

The VREF value is given by the datasheet

TPS43000 electrical characteristics

error amplifier

PARAMETER	TEST CONDITIONS		MIN	TYP	MAX	UNIT
VREG, regulation voltage (COMP/FB pin)	1.8 V < VIN < 6 V		784	800	816	mV
	VIN = 3.5 V		788	800	812	
FB input current	V_{FB} = 800 mV		−150	−10	150	nA
Sourcing current (out of COMP)	V_{FB} = (VREG − 100 mV),	V_{COMP} = 0 V,		−2.0	−0.5	mA
Sinking current (into COMP)	V_{FB} = (VREG + 100 mV),	V_{COMP} = 2 V	0.5	1.2		mA
Maximum ouput voltage (COMP pin)	V_{FB} = 0 V,	I_{COMP} = −100 μA	1.6	2.0		V
Minimum output voltage (COMP pin)	V_{FB} = 2 V,	I_{COMP} = +100 μA		70	120	mV
Unity gain bandwidth	See Note 1			5		MHz

So we've got

VREF $= \mathit{0.8}$

Setting PWM Controller's Parameters (Example)

The VP (sawtooth signal amplitude) can be calculated from the characteristics below.

TPS43000 electrical characteristics

PWM

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
BUCK threshold voltage	BUCK configured if $V_{BUCK} > 1$ V	0.4	0.7	1.0	V
BUCK pull-down current			0.5	1.0	µA
BUCK maximum duty cycle	$V_{FB} = 0$ V	100%			
BOOST maximum duty cycle	BUCK grounded, $V_{FB} = 0$ V	70%	90%		
Minimum duty cycle	$V_{FB} = 2$ V			0%	
CCM threshold voltage	Continuous conduction allowed if $V_{CCM} > 1$ V	0.4	0.7	1.0	V
CCM pull-down current			0.5	1.0	µA
BUCK rectifier zero current threshold voltage	Measured from SWP to GND	−28	−12	0	mV
BOOST rectifier zero current threshold voltage	Measured from SWP to VOUT, BUCK grounded	0	14	32	mV
Delay to termination of P-channel gate drive time	Measured at PDRV, BUCK grounded		200	300	ns

from eq. (3)

$$VP = \Delta V_{FB} / \Delta d$$

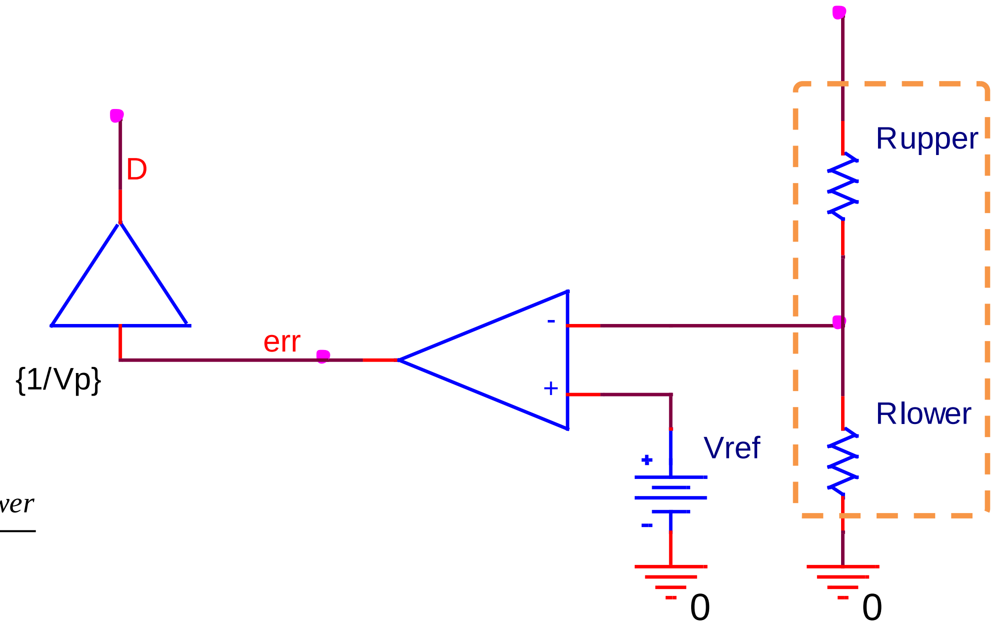
- from the datasheet , $\Delta V_{FB} = (2-0) = 2V$, and $\Delta d = (0.9-0) = 0.9$

$$VP = 2 / 0.9 = 2.2$$

2 Programming Output Voltage: Rupper, Rlower

- Use the following formula to select the resistor values.

$$V_{out} = V_{ref}\left(1 + \frac{R_{upper}}{R_{lower}}\right) \qquad (4)$$



Example

Given: $V_{out} = 12V$

$V_{ref} = 0.8$

$R_{lower} = 10k$

then:

$$R_{upper} = \frac{(V_{OUT} - V_{REF}) \times R_{lower}}{V_{REF}}$$

$R_{upper} = 140k$

2 Programming Output Voltage: Rupper, Rlower

Bee Technologies

- This calculation could be completed by using **the Boost Converter Calculator (Excel sheet)**.
- After input all the boost converter specs and the *Rlower* value then *Rupper* is automatically calculated

Boost Converter Calculator (Excel sheet)

The following specs are needed to calculate the power stage:

Spec:	$V_{in,max}$	3.63	V
	$V_{in,min}$	2.97	V
	V_{out}	12	V
	$V_{out,ripple}$	0.18	V ; *1% ripple value*
	$I_{o,max}$	1.5	A
	$I_{o,min}$	0.2	A

The power stage spec values are input

The following specs are needed to calculate the controller stage:

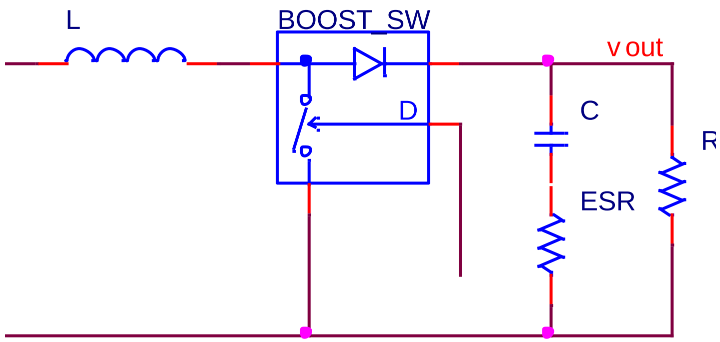
❶	V_{REF}	0.8	V
	Vp	2.2	V
	f_{OSC}	300	kHz

The controller spec values are input

❷	*Rlower*	10	kΩ
	Rupper	140	kΩ

Input the Rlower value, then ***Rupper is auto-calculated***

3 Inductor Selection: L, R_{LS}



Inductor Value

- The output inductor value is selected to set the converter to work in CCM (Continuous Current Mode) for all load current conditions.
- Calculated by

$$L_{CCM} \geq \frac{D_{\min} \cdot (1 - D_{\min})^2 \cdot V_{OUT}}{2 \cdot f_{osc} \cdot I_{O,\min}} \quad (5)$$

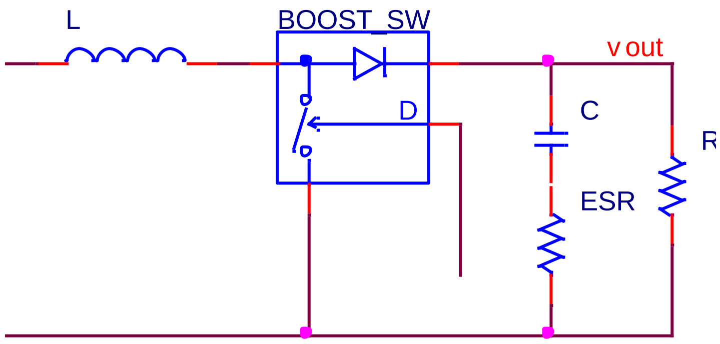
- *with*

$$\Delta I_L = \frac{V_{in,\min} \cdot D_{\max}}{L \cdot f_{osc}} \quad (6)$$

Where

- L_{CCM} is the inductor that make the converter to work in CCM.
- D_{max} is the maximum duty cycle; D_{max}=1- $V_{in,min} / V_{OUT}$
- R_{Ls} is load resistance at the minimum output current ($I_{o,min}$)
- f_{osc} is switching frequency
- ΔI_L is inductor ripple current

3 Inductor Selection: L, R_{LS} (Example)



Inductor Value

from eq. (5)

$$L_{CCM} \geq \frac{D_{\min} \cdot (1 - D_{\min})^2 \cdot V_{OUT}}{2 \cdot f_{osc} \cdot I_{O,\min}}$$

Given:

- $V_{in,max}$ = 3.63V (3.3V+10%), V_{out} = 12V, $I_{o,min}$ = 0.2A
- D_{min} = 1- $V_{in,max} / V_{out}$ = 0.7
- f_{osc} = 300kHz

Then:

- $L_{CCM} \geq$ 64 (uH),
- L = 68 (uH) is selected

③ Inductor Selection: L, R_{LS} (Example)

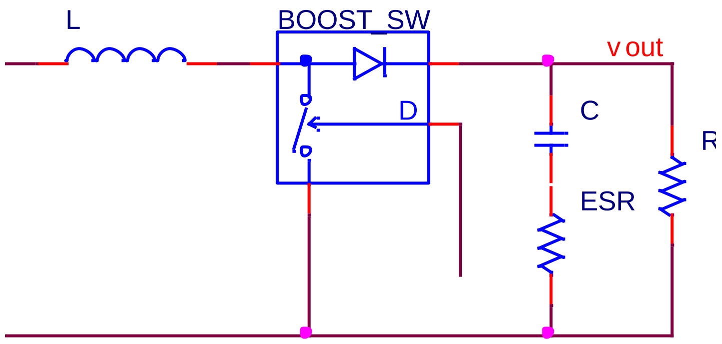
- This calculation could be completed by using **the Boost Converter Calculator (Excel sheet)**.
- After input all the known parameters, this sheet will suggest the inductor L value, using eq. (5)

	D_{max}	0.75		; = 1- $V_{in,min}/V_{out}$
	D_{min}	0.70		; = 1- $V_{in,max}/V_{out}$
❸	$L >$	6.4	uH	; suggested inductor L value (from eq.5)
	$L =$	6.8	uH	; the selected inductor L value
	RLs	10	mΩ	; the selected inductor, series resistance value
	ΔI_L	1.10E+00	A	; calculated inductor ripple current (from eq.6)

D_{max} and D_{min} are auto-calculated

The excel sheet suggests an inductor value, by using eq. (5). Then input your inductor L value (> suggested value), and RLs value of the inductor for further calculation.

4 Capacitor Selection: C, ESR



Capacitor Value

- The minimum allowable output capacitor value should be determined by

$$C \geq \frac{D_{max} \cdot I_{o,\,max}}{V_{out,\,ripple} \cdot f_{OSC}} \qquad (7)$$

- In addition, the capacitor must be able to handle the current more than

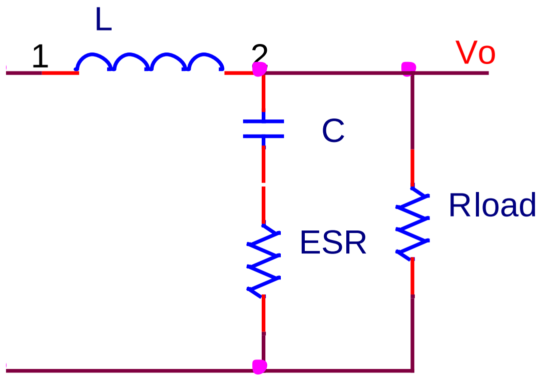
$$I_{C,\,Rated} \approx \frac{\Delta I_L}{2} \qquad (8)$$

  - Where ΔI_L is calculated by eq. (6)

- The ESR of the output capacitor adds some more ripple, so it should be limited by following equation:

$$ESR \leq \frac{V_{out,\,ripple}}{I_C} \qquad (9)$$

4 Capacitor Selection: C, ESR (Example)



Capacitor Value

From eq. (7)

$$C \geq \frac{D_{\max} \cdot I_{o,\max}}{V_{out,\,Ripple} \cdot f_{OSC}}$$

and eq. (8) and eq. (9)

$$I_C \approx \frac{\Delta I_L}{2} \qquad ESR \leq \frac{V_{out,\,ripple}}{I_C}$$

Given:

- $D_{\max}$ = 0.75 V
- $I_{o,\ max}$ = 1.5 A
- $V_{\text{out,ripple}}$ = 0.18 V

Then:

- $C \geq$ 20.9 (μF)

In addition:

- $I_{C,Rated} \approx 550mA$
- $ESR \leq$ 27mΩ

Capacitor Selection: C, ESR (Example)

- This calculation could be completed by using **the Boost Converter Calculator (Excel sheet)**.
- After input all the known parameters, this sheet will suggest the capacitor C and ESR value, using eq. (7) and eq. (9).

❹	$C \geq$	20.9	uF	; eq. (7) suggested value
	C	1410	uF	; the selected Capacitor C value
	$ESR <$	0.027	Ω	; eq. (9) suggested value
	$ESR =$	0.027	Ω	; the selected capacitor ESR value
	$I_{C,Rated} \approx$	0.55	A	; Rated ripple current

The excel sheet suggests an capacitor value, by using eq. (7) and ESR value by using eq. (9). Then input your capacitor C Value and the capacitor's ESR value for further calculation. The capacitor's rated current should be more than the suggested value I_C

4 Capacitor Selection: C, ESR (Example)

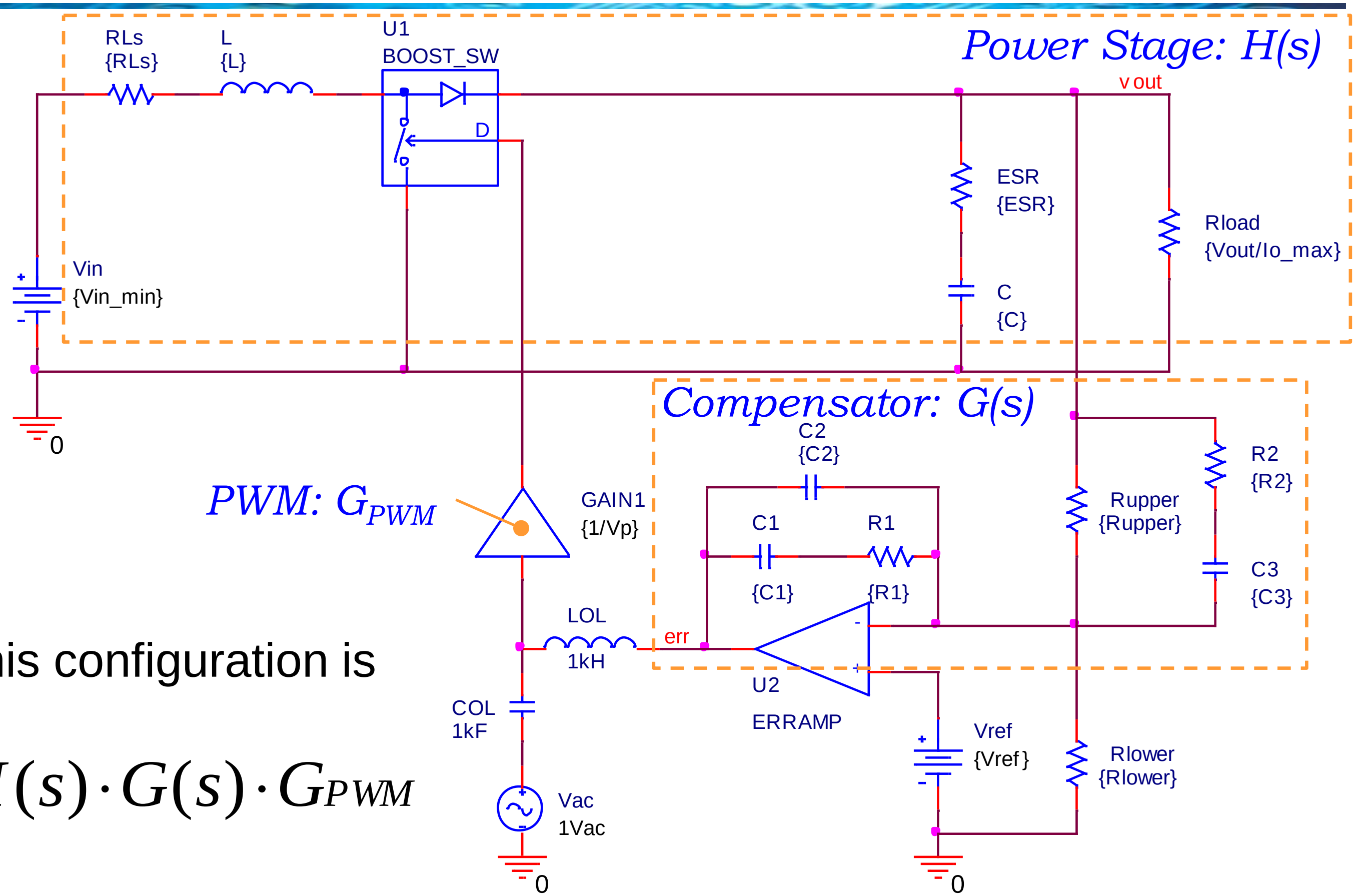
- A SMD type electrolytic capacitor from NIPPON CHEMI-CON, part no. EMZJ160ADA471MHA0G is selected with the following characteristics.

<u>EMZJ160ADA471MHA0G</u>

$C =$	$470\ uF$
Vdc	$16\ V$
$ESR =$	$0.08\ \Omega$
$Rated\ Ripple\ Current$	$0.85\ A_{rms}$

- The suggested ESR should be less than 27 mΩ, three of these part will be put in parallel to meet the converter specs.
- So we select the capacitor C value = 470uF $\times$ 3 = 1410 uF, with ESR = 0.08Ω / 3 = 0.027Ω

5 Stabilizing the Converter



- Loop gain for this configuration is

$$T(s) = H(s) \cdot G(s) \cdot G_{PWM}$$

- The purpose of the compensator *G(s)* is to tailor the converter loop gain (frequency response) to make it stable when operated in closed-loop conditions.

5 Stabilizing the Converter (Example)

Converter parameters

PARAMETERS:

Vin_min = 2.97

Vout = 12V

Io_max = 1.5A

Vref = 0.8 ①

Vp = 2.2

Rlower = 10k ②

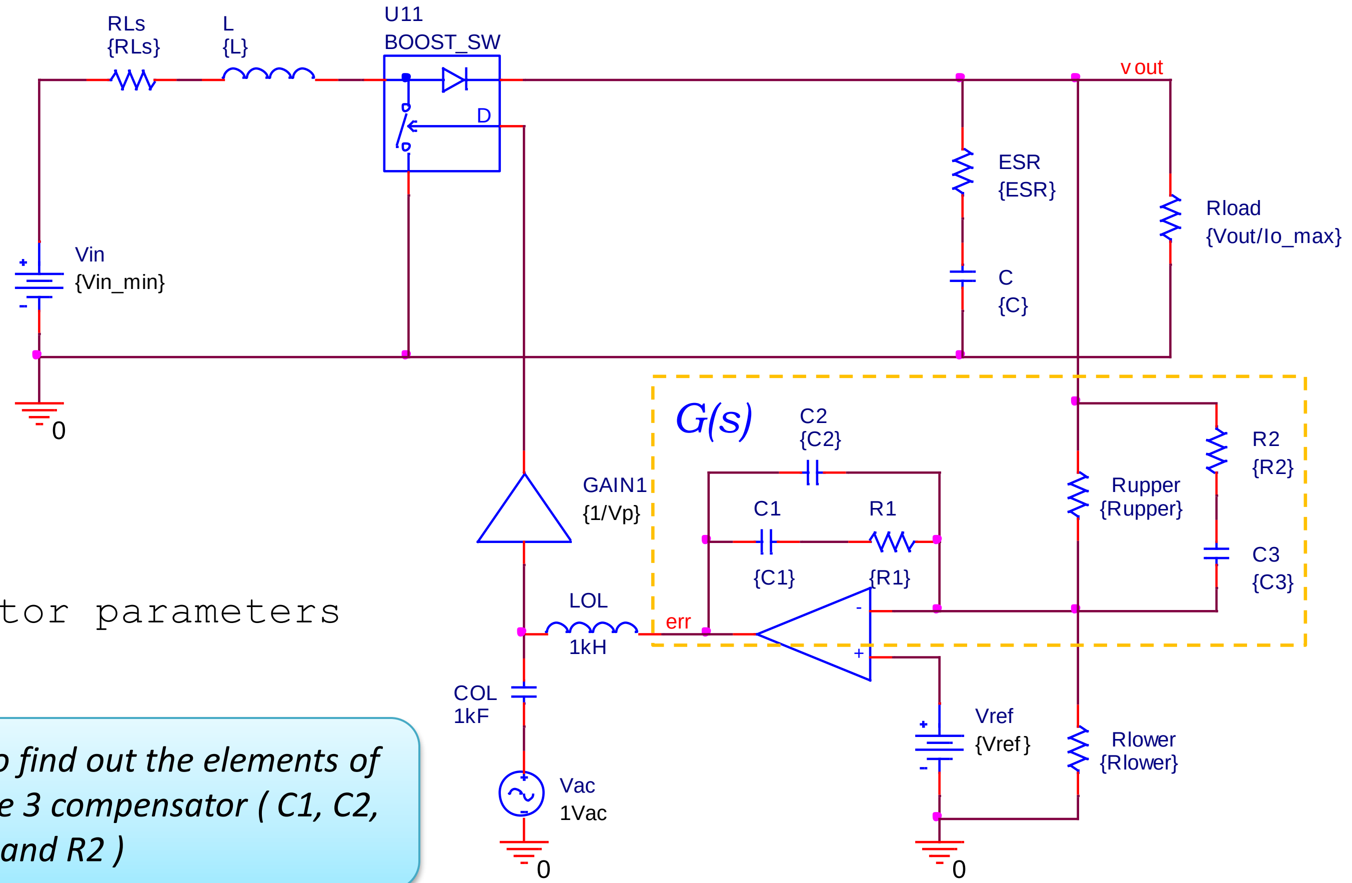
Rupper = 140k

L = 6.8u ③

RLS = 10m

C = 1410u ④

ESR = 27m



Type 3 compensator parameters

PARAMETERS:

C1 = ?

C2 = ?

C3 = ?

R1 = ?

R2 = ?

Task: to find out the elements of the Type 3 compensator (C1, C2, C3, R1, and R2)

5 Stabilizing the Converter (Example)

Frequency Response without Compensator.

$$T(s) = H(s) \cdot G_{PWM}$$

Converter parameters

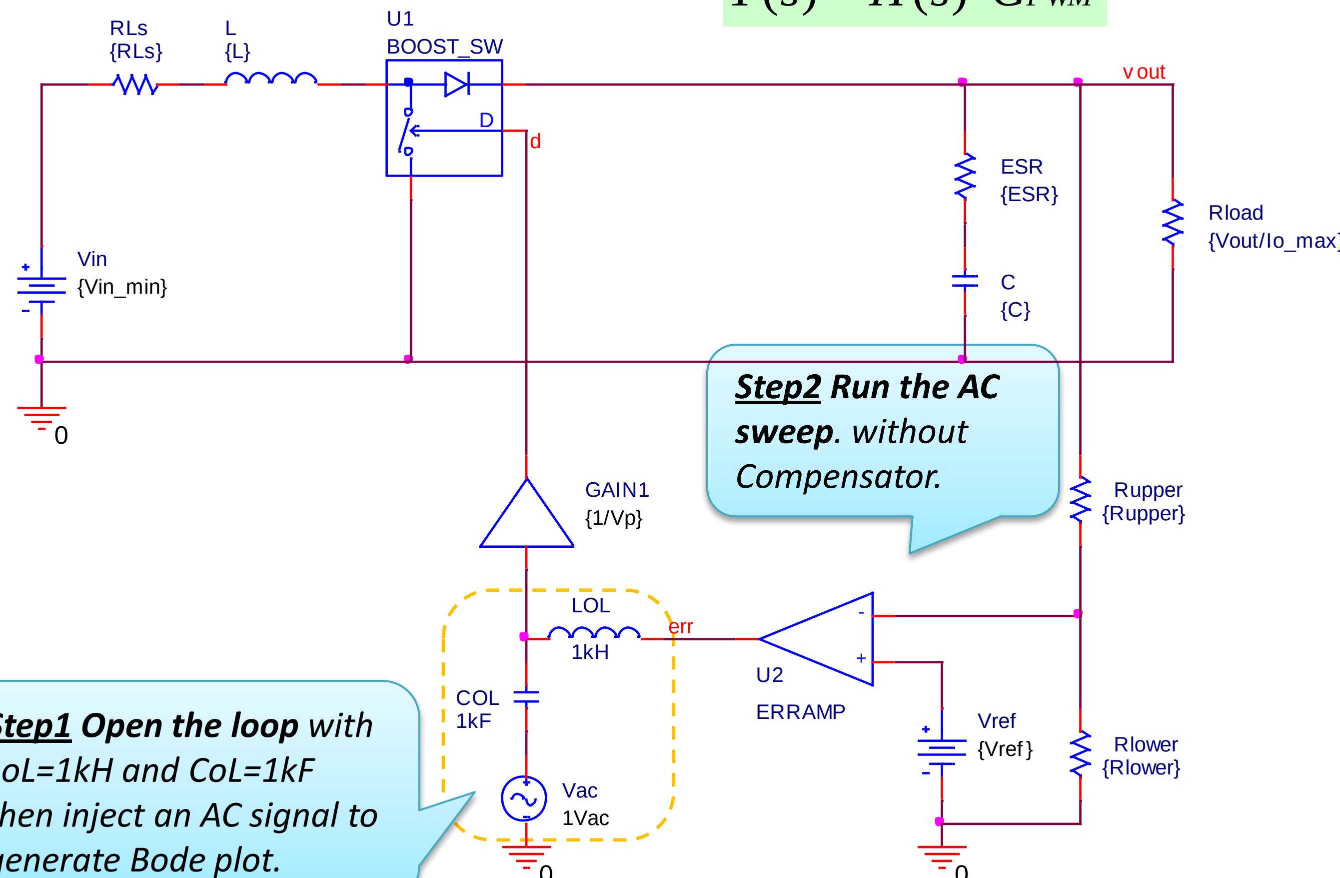
PARAMETERS:

Vin_min = 2.97

Vout = 12V

Io_max = 1.5A

1. Vref = 0.8
   Vp = 2.2
2. Rlower = 10k
   Rupper = 140k
3. L = 6.8u
   RLS = 10m
4. C = 1410u
   ESR = 27m



Step2 ***Run the AC sweep****. without Compensator.*

Step1 ***Open the loop*** *with LoL=1kH and CoL=1kF then inject an AC signal to generate Bode plot.*

※C1=1kF is AC shorted, and C2 1fF is AC opened (or Error-Amp without compensator).

5 Stabilizing the Converter (Example)

- This calculation could be completed by using **the Boost Converter Calculator (Excel sheet)**.
- After input all the known parameters, this sheet will suggest the crossover frequency f_c value, and the maximum input voltage $V_{in,max}$.

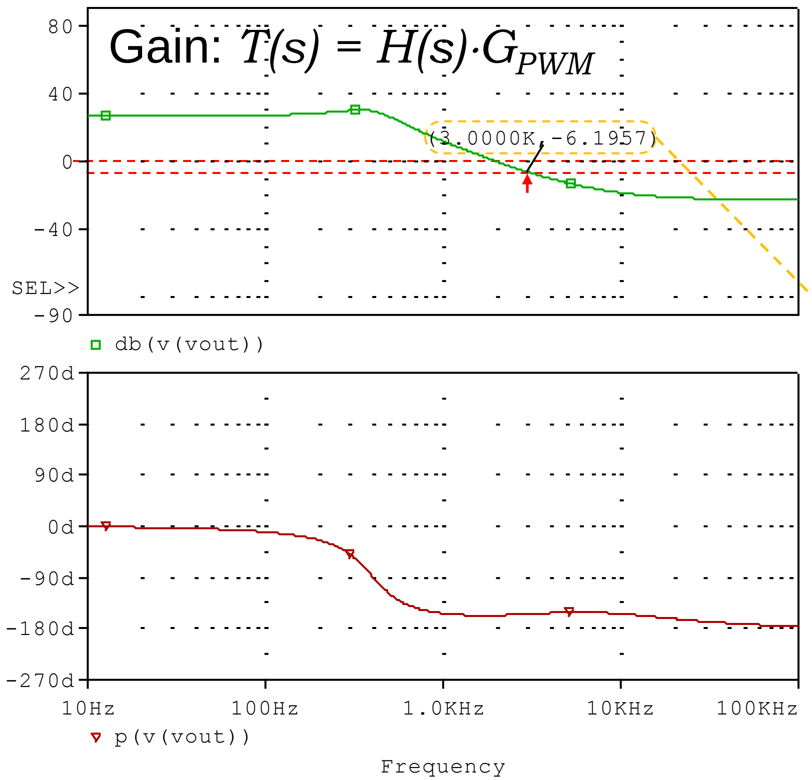
Type 3 Compensator Calculator

$R_{load,min}$	8	Ω	; $= V_{out}/I_{o,min}$
$f_c <$	3440.91	Hz	; $fc <$ 0.3 times RHPZ, f_{z2}
$f_c =$	3000	Hz	; select the value of fc
$V_{in,max} <$	7.38	V	; $V_{\mathrm{in,max}}$ suggested value

***Step3* Select a crossover frequency-f_c**
the maximum f_c is automatically calculated from the boost converter spec and condition. Select the value a little lower than the suggested value.

The $V_{in,max}$ suggested value shows the maximum input voltage that the converter could be used.

5 Stabilizing the Converter (Example)



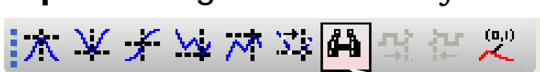
*Frequency Response **without** Compensator.*

***Step4** Read the Gain value (dB) at the f_C from the Bode plot, Then put the values to the sheet.*

Compensator:

G @ f_c	-6.2 dB	; read from the simulation result
G	2.042	; compensation gain

Tip: To bring cursor to the $fc = 3kHz$ type " **sfxv(3k)** " in Search Command.



Cursor Search

5 Stabilizing the Converter (Example)

- This calculation could be completed by using **the Boost Converter Calculator (Excel sheet)**.
- After input all the known parameters, this sheet will suggest the **C1, C2, C3, R1, and R2** values.

Compensator:

$f_{z,double}$	402	Hz	; double zero use to compensate the LC filter peak (resonant)
f_{p1}	4181	Hz	; a first pole use to compensate an ESR effect
f_{p2}	11470	Hz	; a second pole use to compensate RHP zero
a	8.39E+13		
c	3.72E+15		

Compensator components:

Step5 ***R C values are suggested,*** *input the values to the elements of compensator.*

❺

C1	**8.259**	**nF**
C2	**0.795**	**nF**
C3	**2.826**	**nF**
R1	**47.9**	**kΩ**
R2	**4.9**	**kΩ**

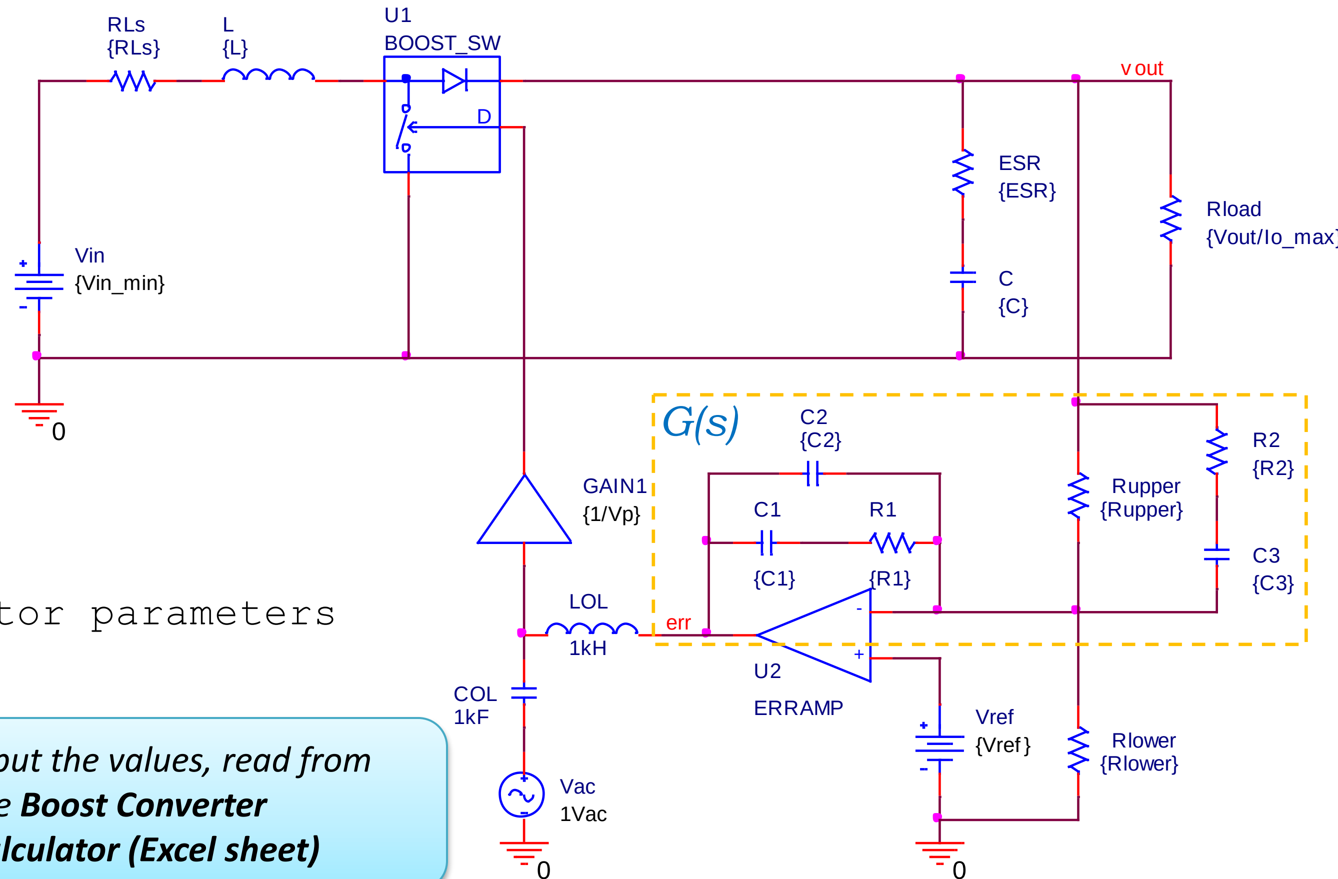
※Please note that the capacitor C value (from 4) needs to be big enough to make $f_{p2} > f_{p1}$ for the best result in calculation.

5 Stabilizing the Converter (Example)

*Frequency Response **with** Compensator.*

Converter parameters

PARAMETERS:
Vin_min = 2.97
Vout = 12V
Io_max = 1.5A
Vref = 0.8
Vp = 2.2 (1)
Rlower = 10k
Rupper = 140k (2)
L = 6.8u
RLS = 10m (3)
C = 1410u
ESR = 27m (4)



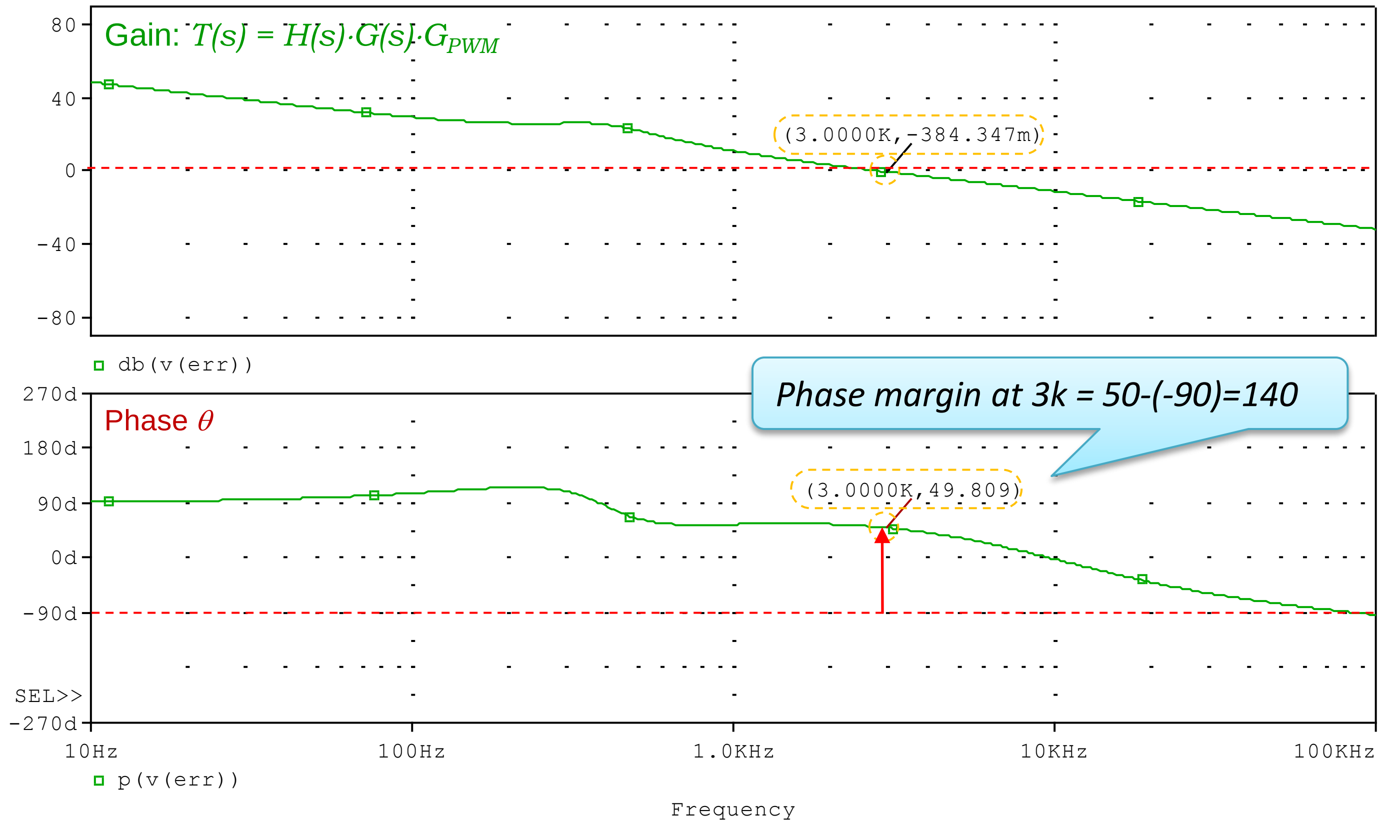
Type 3 compensator parameters

PARAMETERS:
C1 = 8.259n
C2 = 795p
C3 = 2.826n
R1 = 47.9k
R2 = 4.9k

*Input the values, read from the **Boost Converter Calculator (Excel sheet)***

5 Stabilizing the Converter (Example)

Gain and Phase responses after stabilizing



- Phase margin = 140 at 3kHz.

Load Transient Response Simulation (Example)

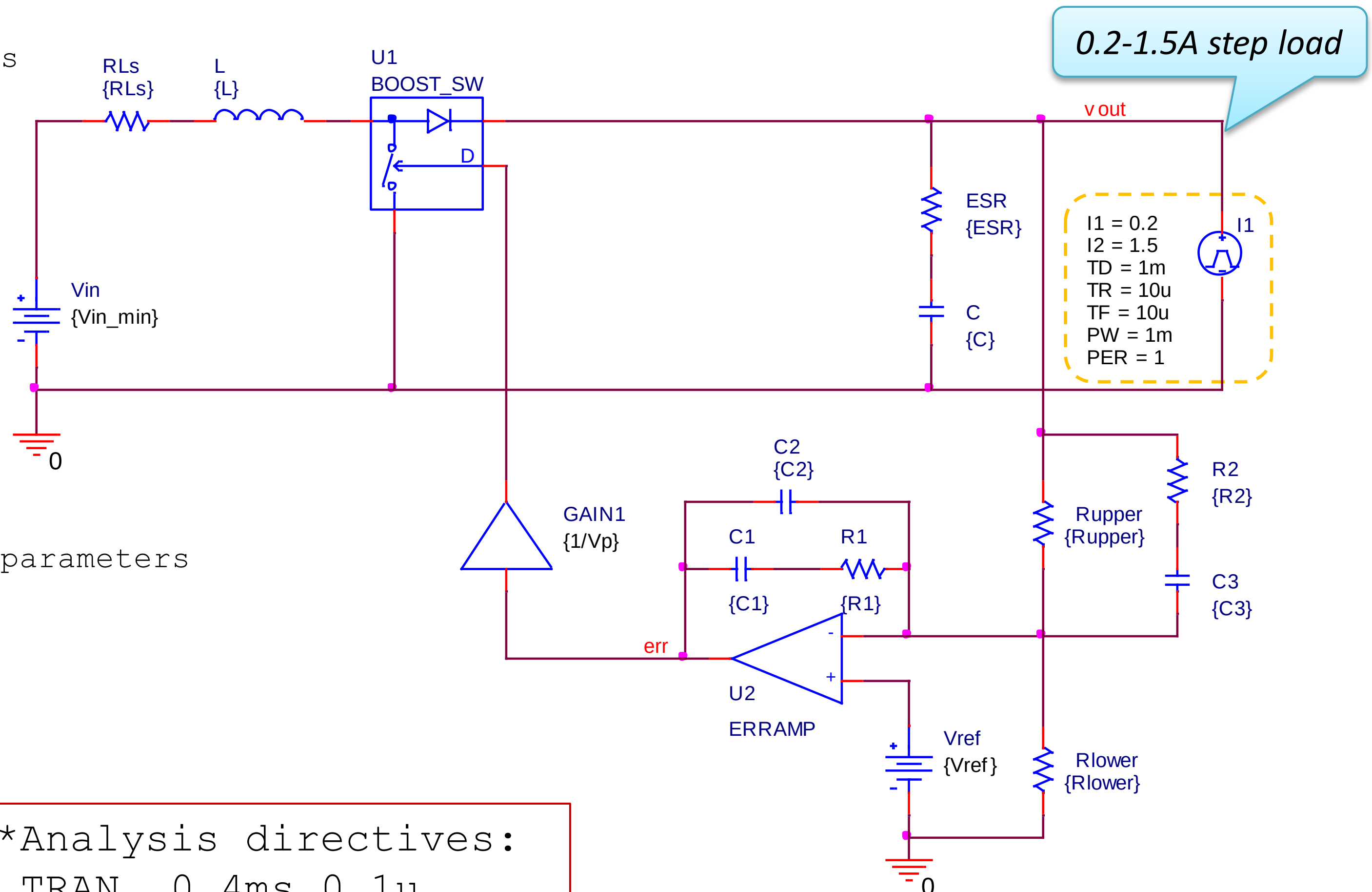
The converter, that have been stabilized, are connected with step-load to perform load transient response simulation.

Converter parameters

PARAMETERS:
- Vin_min = 2.97
- Vout = 12V
- Io_max = 1.5A
- Vref = 0.8
- Vp = 2.2
- Rlower = 10k
- Rupper = 140k
- L = 6.8u
- RLS = 10m
- C = 1410u
- ESR = 27m

Type 3 compensator parameters

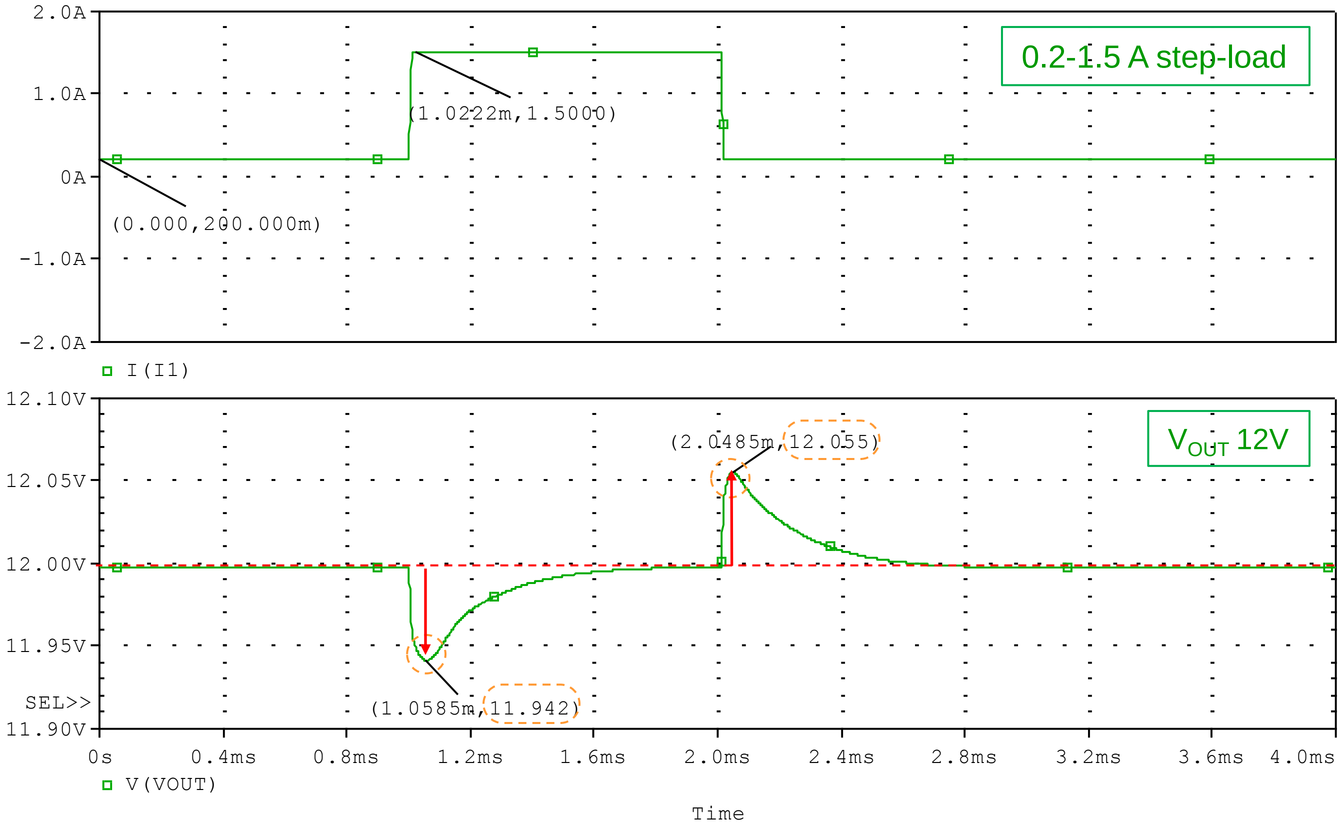
PARAMETERS:
- C1 = 8.259n
- C2 = 795p
- C3 = 2.826n
- R1 = 47.9k
- R2 = 4.9k




```
*Analysis directives:
.TRAN  0 4ms 0 1u
```

5 Stabilizing the Converter (Example)

Step-load transient responses after stabilizing



- The simulation result shows undershoot and overshoot voltages caused by step-load, that are below 120mV or less than 1% of the output.

A. Boost Converter Calculator (Excel sheet) 1/3

Boost Converter Calculator (Excel sheet)

The following specs are needed to calculate the power stage:

Spec:	$V_{in,max}$	3.63	V	; +10% of 3.3V
	$V_{in,min}$	2.97	V	; -10% of 3.3V
	V_{out}	12	V	
	$V_{out,ripple}$	0.18	V	; 1.5% ripple value
	$I_{o,max}$	1.5	A	
	$I_{o,min}$	0.2	A	

A. Boost Converter Calculator (Excel sheet) 2/3

The following specs are needed to calculate the controller stage:

❶	V_{REF}	0.8	V	
	Vp	2.2	V	
	f_{OSC}	300	kHz	
❷	$Rlower$	10	kΩ	
	$Rupper$	140	kΩ	
	D_{max}	0.75		; $= 1- V_{in,min}/V_{out}$
	D_{min}	0.70		; $= 1- V_{in,max}/V_{out}$
❸	$L >$	6.4	uH	; suggested inductor L value
	$L =$	6.8	uH	; the selected inductor L value
	$R_{Ls} =$	10.0	mΩ	; the selected inductor, series resistance value
	ΔI_L	1.10E+00	A	; calculated inductor ripple current
❹	$C \geq$	20.9	uF	; eq. (7) suggested value
	C	1410	uF	; the selected capacitor C value
	$ESR \leq$	0.027	Ω	; eq. (9) suggested value
	$ESR =$	0.027	Ω	; the selected capacitor ESR value
	$I_{C,Rated} =$	5.48E-01		; Rated ripple current

A. Boost Converter Calculator (Excel sheet) 3/3

Type 3 Compensator Calculator

$R_{load,min}$	8	Ω	; $= V_{out}/I_{o,min}$
$f_c <$	3440.91	Hz	; $f_C <$ 0.3 times RHP zero
$f_c =$	3000	Hz	; the selected f_C value
$V_{in,max} <$	7.38	V	; $V_{in,max}$ suggested value

Compensator:

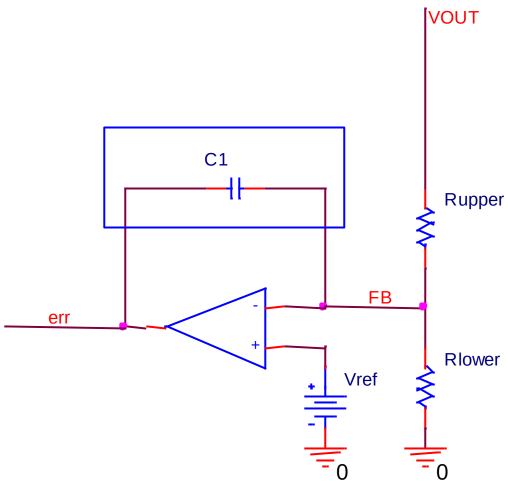
G @ f_c	-6.2	dB	; read from the simulation result
G	2.042		; compensation gain
$f_{z,double}$	402	Hz	; double zero use to compensate the LC filter peak (resonant)
f_{p1}	4181	Hz	; a first pole use to compensate an ESR effect
f_{p2}	11470	Hz	; a second pole use to compensate RHP zero
a	8.39E+13		
c	3.72E+15		

Compensator components:

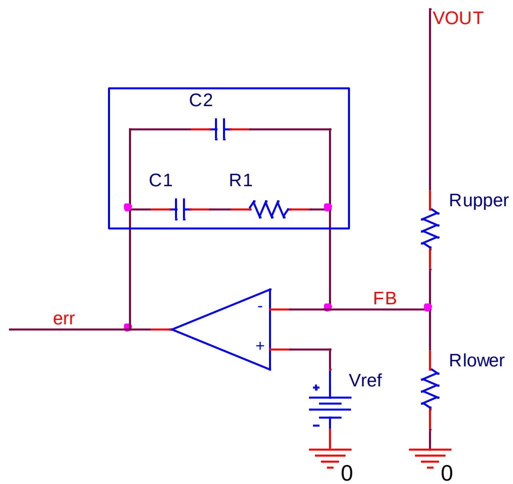
❺

C1	**8.259**	**nF**
C2	**0.795**	**nF**
C3	**2.826**	**nF**
R1	**47.9**	**kΩ**
R2	**4.9**	**kΩ**

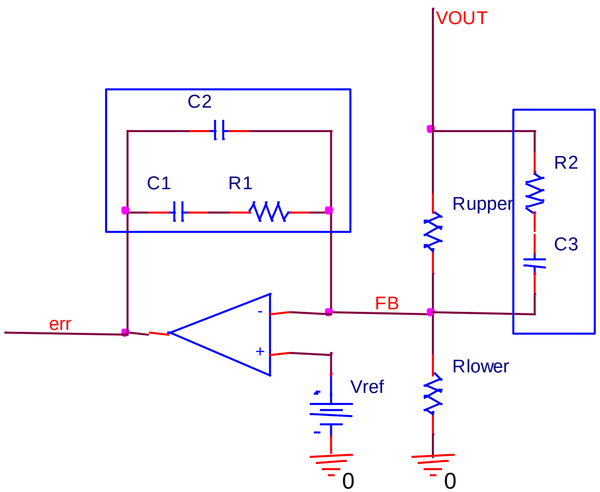
B. Feedback Loop Compensator



Type1 Compensator



Type2 Compensator



Type3 Compensator

- Because the boost converter is a 2nd order system, so the Type3 compensator are needed

C. Simulation Index

Simulations	Folder name
1. Frequency Response without a Compensator............................	freq_resp
2. Frequency Response with a Type3 Compensator......................	freq_resp-comp
3. Step-load Transient Response..	step-load

Libraries :
1. ..¥boost_sw.lib
2. ..¥erramp.lib

Tool :
- Boost Converter Calculator (Excel sheet)

  Boost_Calculator.xls