PSIM

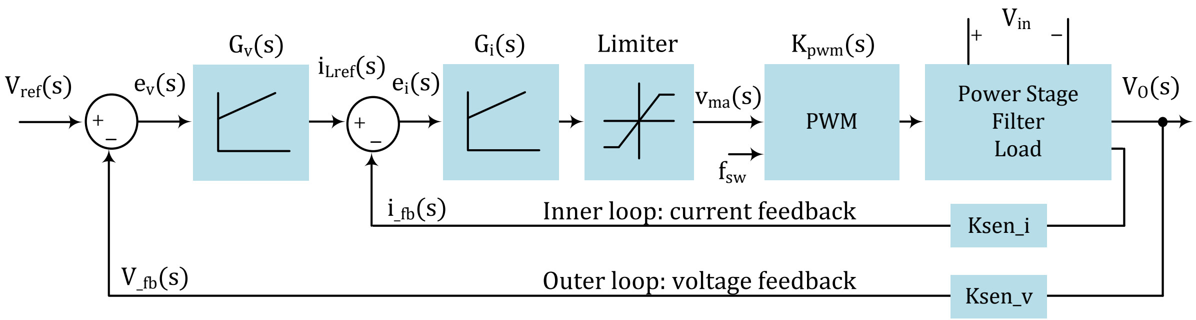
TUTORIAL

Control Loop Design Using Script Functions

April 2020

PSIM's script functions provide the capability for users to design control loops and display the Bode plots of the plant, controller, and loop transfer functions.

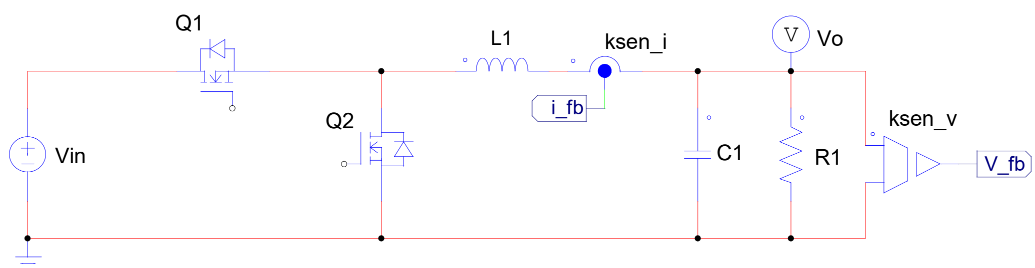
In this tutorial, design of the inner current loop and outer voltage loop of a buck converter using script functions is described. The control block diagram is shown below.



For more information on how to use script functions, please refer to the document "Tutorial – How to User Script Functions.pdf".

Buck Converter Circuit

The buck converter is shown below:



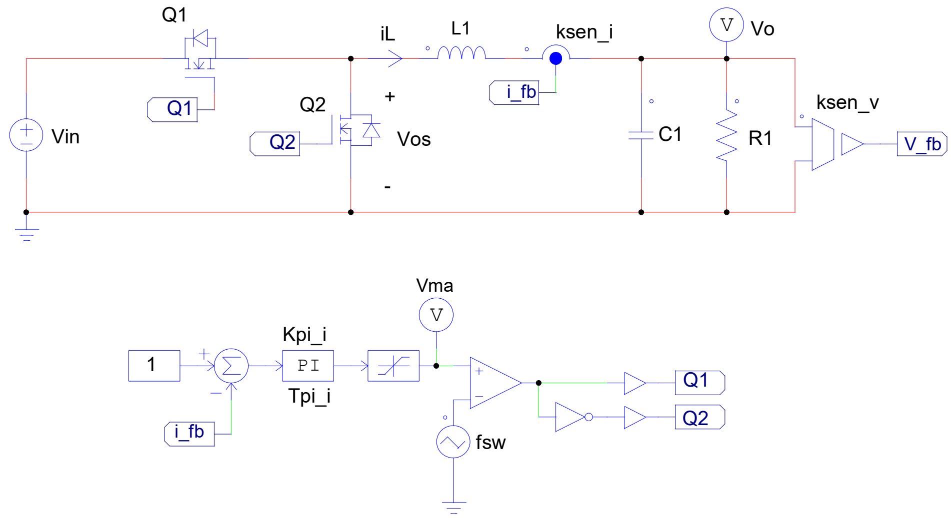
The operating conditions are:

- Vin = 250 V; Vo = 100 V
- L1 = 200 uH; C1 = 245 uF; R1 = 0.6 Ohm
- Current and voltage sensors: ksen_i = 1/165; ksen_v = 1/100
- Switching frequency: fsw = 20 kHz

There are two control loops: inner current loop, and outer voltage loop. The first step is to design the inner current loop. After that, the voltage loop will be designed.

Current Loop Design

The buck converter with the inner current loop is shown below.



A PI controller is used for the current loop. The following script is used to design the PI parameters.

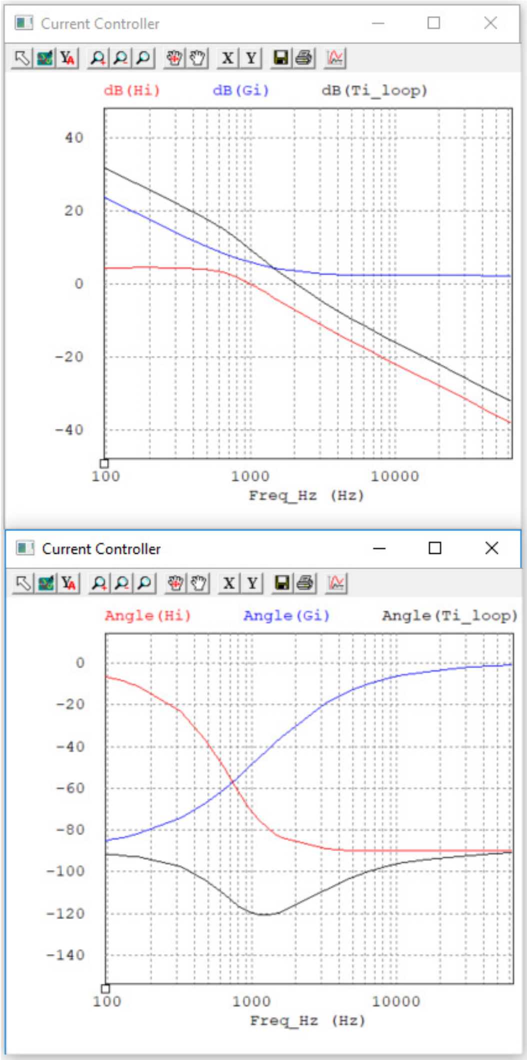
```
// Buck converter - current loop design
PI = 3.14159;

// Parameters
Vin = 250;
L1 = 200u;
C1 = 245u;
R1 = 0.6;

Ksen_i = 1/165;
Ksen_v = 1/100;

// PWM gain: Kpwm = Vin/Vcarrier, with Vcarrier = 1
Kpwm = Vin;

fsw = 20k;

// Desired current loop gain-cross-over frequency fx_i and phase margin
fx_i = 2k;
phase_margin_i = 64;  // in deg.

// Current PI controller
Kpi_i = 1.30253;
Tpi_i = 140.9973u;

// Plant: Hi(s) = iL / Vos
Hi = formula(1/(s*L1 + R1/(s*R1*C1+1)));

// Current PI: Gi = Ki * (1+sTi) / (sTi)
Gi = formula(Kpi_i*(1+s*Tpi_i)/(s*Tpi_i))

// Current loop transfer function Ti_loop
Ti_loop = Hi*Gi*Ksen_i*Kpwm
```

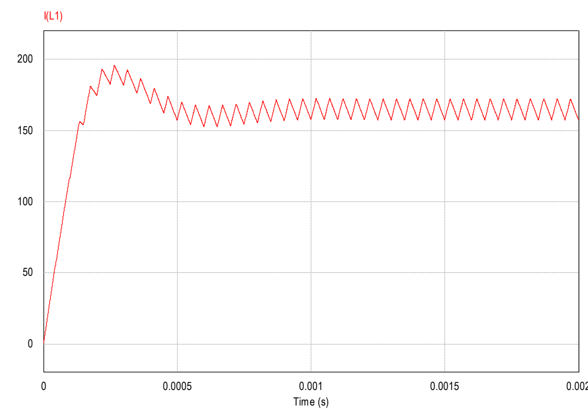
```
// Find Ti_loop at fx_i
s_fx_i = Complex(0, 2*PI*fx_i);
Ti_loop_fx = eval(Ti_loop, s=s_fx_i);
Ti_loop_fx_amp = abs(Ti_loop_fx);
Ti_loop_fx_angle = angle(Ti_loop_fx)*180/PI;   // in deg.

phase_margin = 180+Ti_loop_fx_angle;     // in deg.

// Bode plot
wmin = 100 *2*PI;
wmax = 50e3 *2*PI;
Freq_rad = ArrayLog(wmin, wmax);  // frequency array (rad/sec) from wmin to wmax, in log scale
Freq_Hz = Freq_rad/(2*PI);  // frequency array (Hz) from fmin to fmax, in log scale

s = Complex(0, Freq_rad);       // Laplace operator

BodePlot("Current Controller", Freq_Hz, Hi, Gi, Ti_loop);    // generate Bode plots for Hi(s), Gi(s), and GiHi(s)
```

The script functions are highlighted in blue for easy inspection. The script does the following:

- Define the plant transfer function Hi(s) = iL / Vos. This expression is obtained from derivation.
- Define the PI controller transfer function Gi(s).
- Obtain the current loop transfer function Ti_loop(s), which is equal to Hi(s)*Gi(s), multiplied by the rest of the gains in the circuit.
- With a switching frequency of 20kHz, let's set the desired gain-cross-over frequency at 2kHz and the phase margin at 64 deg. Through trial-and-error, first adjust Tpi_i manually until the phase margin is 64 deg. Then adjust Kpi_i until the loop transfer function amplitude Ti_loop_fx_amp is 1.

From the procedure above, we obtain: Kpi_i = 1.30253, and Tpi_i = 140.9973u. The Bode plots Hi(s), Gi(s), and Ti_loop(s) are shown below on the left.



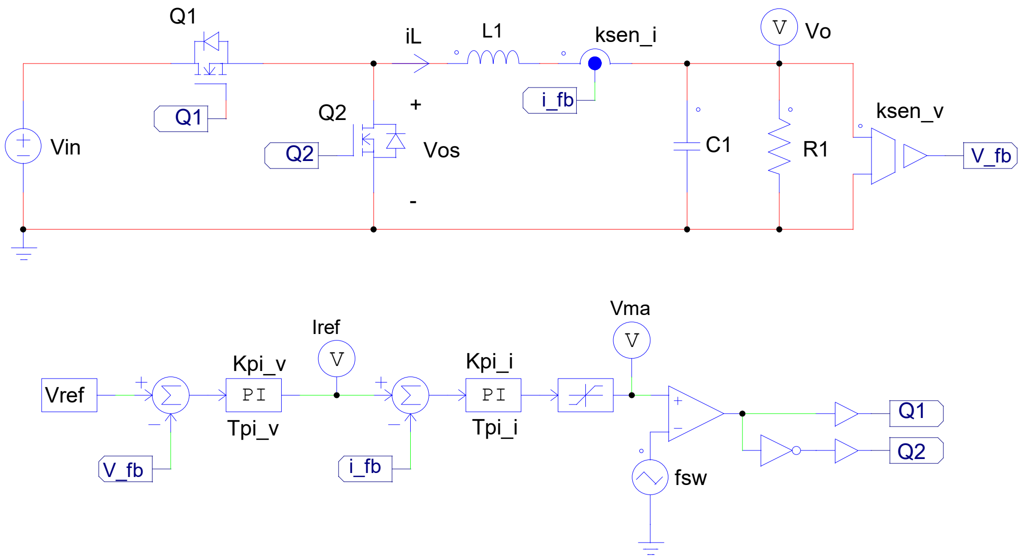


The Bode plots show that the current loop has the desired gain-cross-over frequency and phase margin.

Using the designed PI parameters, we can perform the time-domain simulation. The current waveform is shown above on the right. The waveform shows a good dynamic response.

Voltage Loop Design

After the current loop is designed, we can proceed to design the voltage loop. The buck converter with both the current loop and voltage loop is shown below.



A PI controller is used for the voltage loop. To design the PI parameters, the following script is written.

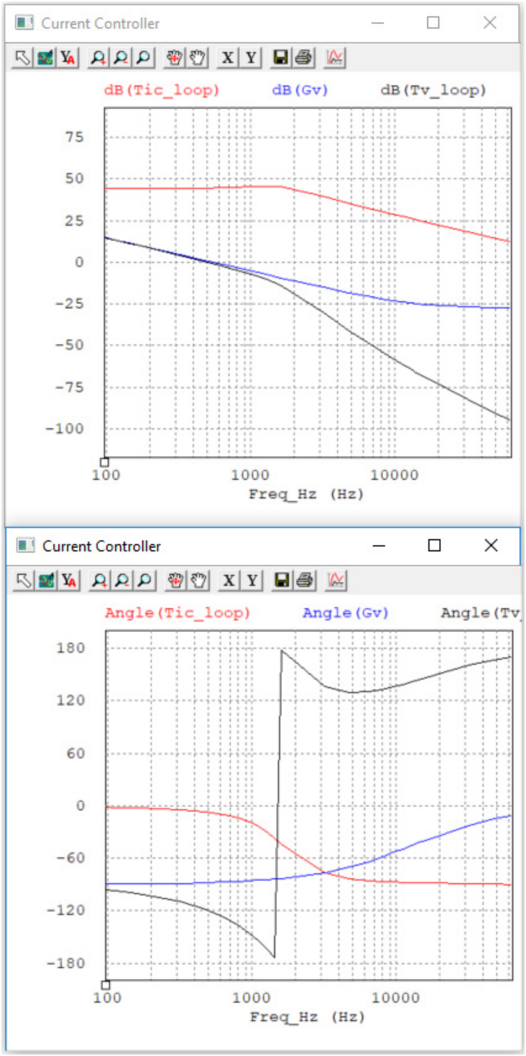
```
// Buck converter - current loop and voltage loop design
PI = 3.14159;

// Parameters
Vin = 250;
L1 = 200u;
C1 = 245u;
R1 = 0.6;

ksen_i = 1/165;
ksen_v = 1/100;

// PWM gain: Kpwm = Vin/Vcarrier, with Vcarrier=1
Kpwm = Vin;

fsw = 20k;

// Desired current loop gain-cross-over frequency fx_i and phase margin
fx_i = 2k;
phase_magin_i = 64; // in deg.

// Current PI controller
Kpi_i = 1.30253;
Tpi_i = 140.9973u;

// Desired voltage loop gain-cross-over frequency fx_v and phase margin
fx_v = 500;
phase_magin_v = 60; // in deg

// Voltage loop PI controller
```

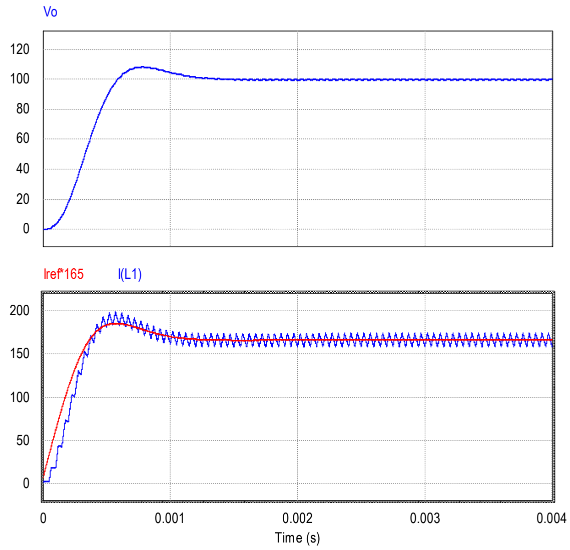
```
Kpi_v = 0.042;
Tpi_v = 12.34u

//------------------- Current Loop ----------------------
// Plant: Hi(s) = iL / Vos
Hi = formula(1/(s*L1 + R1/(s*R1*C1+1)));

// Current loop PI: Gi = Ki * (1+sTi) / (sTi)
Gi = formula(Kpi_i*(1+s*Tpi_i)/(s*Tpi_i))

// Current loop transfer function Ti_loop
Ti_loop = Hi*Gi*ksen_i*Kpwm

// Current closed loop transfer function Tic_loop
Tic_loop = 1/ksen_i*(Ti_loop/(1+Ti_loop));

//------------------- Voltage Loop ----------------------
// Plant: Hv(s) = Vo / iL
Hv = formula(R1/(s*R1*C1+1));

// Voltage loop PI: Gv = Kv * (1+sTv) / (sTv)
Gv = formula(Kpi_v*(1+s*Tpi_v)/(s*Tpi_v))

// Voltage loop transfer function Tv_loop
Tv_loop = Hv*Gv*ksen_v*Tic_loop

// Find Ti_loop at fx_v
s_fx = Complex(0, 2*PI*fx_v);
Tv_loop_fx = eval(Tv_loop, s=s_fx);
Tv_loop_fx_amp = abs(Tv_loop_fx);
Tv_loop_fx_angle = angle(Tv_loop_fx)*180/PI;   // in deg.

phase_margin = 180+Tv_loop_fx_angle;   // in deg.

// Bode plot
wmin = 100 *2*PI;
wmax = 50e3 *2*PI;
Freq_rad = ArrayLog(wmin, wmax);  // frequency array (rad/sec) from wmin to wmax, in log scale
Freq_Hz = Freq_rad/(2*PI);        // frequency array (Hz) from fmin to fmax, in log scale

s = Complex(0, Freq_rad);         // Laplace operator

BodePlot("Current Controller", Freq_Hz, Tic_loop, Gv, Tv_loop);    // generate Bode plots
```

In the script, the closed loop transfer function of the current loop, Tic_loop(s), is obtained and is used for the design of the outer voltage loop.

Let's set the desired gain-cross-over frequency at 500Hz and the phase margin at 60 deg. for the voltage loop. The process of designing the voltage PI parameters is similar to that of the current loop. That is, through trial-and-error, adjust Tpi_v until the phase margin is 60 deg. Then adjust Kpi_v until the gain Tv_loop_fx_amp is 1.

We obtain: Kpi_v = 0.042, and Tpi_i = 12.34u. The Bode plots of Tic_loop(s), Gv(s), and Tv_loop(s) are shown below on the left.





The Bode plots show that the voltage loop has the desired gain-cross-over frequency and phase margin.

Using the designed voltage loop PI parameters, we can perform the time-domain simulation. The voltage and current waveform are shown above on the right. The waveforms show a good dynamic response.

This example demonstrates that PSIM's script functions provide a very powerful way to perform various calculations, including control loop design.