Reference

[1] *JESSE B. HOAGG and DENNIS S. BERNSTEIN*, 'Nonminimum Phase Zeros - Much To Do about Nothing', JUNE 2007 IEEE CONTROL SYSTEMS MAGAZINE.

[2] *D. M. Mitchell*, 'Understanding the Right-Half-Plane Zero in Small-Signal DC-DC Converter Models' IEEE Power Electronics Society NEWSLETTER, January 2001.

[3] *Santanu Kapat, Amit Patra, Member, IEEE, and Soumitro Banerjee, Senior Member, IEEE,* "A Current-Controlled Tristate Boost Converter With Improved Performance Through RHP Zero Elimination" IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 24, NO. 3, MARCH 2009.

[4] *Santanu Kapat, Amit Patra, Member, IEEE, and Soumitro Banerjee, Senior Member,* "A Novel Current Controlled Tri-State Boost Converter with Superior Dynamic Performance" Circuits and Systems, 2008. ISCAS 2008. IEEE International Symposium on May 2008.

[5] *Kanakasabai Viswanathan, Member, IEEE, Ramesh Oruganti, Senior Member, IEEE, and Dipti Srinivasan, Senior Member, IEEE,* "Dual-Mode Control of Tri-State Boost Converter for Improved Performance" IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 20, NO. 4, JULY 2005.

[6] *Han-Hsiang Huang, Chi-Lin Chen, Dian-Rung Wu, and Ke-Horng Chen, Senior Member, IEEE* "Solid-Duty-Control Technique for Alleviating the Right-Half-Plane Zero Effect in Continuous Conduction Mode Boost Converters" IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 27, NO. 1, JANUARY 2012.

[7] Ceylon Electricity Board Statistical Report 2012.

[8] Power electronics converters applications and design, 3rd Edition, Mohan, Undeland, Robbins.

[9] *Ramón Leyva, Member IEEE, Pedro Garcés, Javier Calvente, Member IEEE and Luis Martínez-Salamero, Member IEEE* "Feedback Linearization Control Applied to a Boost Power Converter"

[10] General Unified Approach to Modelling Switching-Converters Power Stages: R.D. Middlebrook and S. Cuk, IEEE PESC 1976, Cleveland, OH, June 8-10

[11] *T. Grote, F. Schafmeister, H. Figge, N. Fröhleke, P. Ide, J. Böcker* "Adaptive Digital Slope Compensation for Peak Current Mode Control"

[12] *Jiri Lettl, Jan Bauer, and Libor Linhart* "Comparison of Different Filter Types for Grid Connected Inverter" PIERS Proceedings, Marrakesh, MOROCCO, March 20-23, 2011

[13] EN 5002 - Power Electronics and Applications – Lecture notes

[14] www.mag-inc.com C058195A2 datasheet

[15] www.infineon.com IPW65R080CFD datasheet

[16] ww1.microchip.com/downloads/en/DeviceDoc/21389D.pdf

Appendix

The detailed calculations and the Matlab codes used in the thesis are given below.

A. Finding the L at the boundary

```
Fsw = 45000; %50 kHz
V0  = 325;
Vd  = 48;
I0_max = 2;
Vrms = 230;
R_max = Vrms/I0_max;
Tsw = 1/Fsw;
D = 1 - Vd/V0;       % this is ccm boundry
I0 = 0.01:0.005:2;
L = (V0 * Tsw * D*(1-D)^2)./(2.*I0);  % since this is the critical L we can
use the same D.
plot(I0,L)
grid on;
```

B. Finding current ripple for a given inductance

```
I0 = 0.2; %this is the I0B
deltaV = 1; %1 volt ripple

L = (V0 * Tsw * D*(1-D)^2)./(2.*I0);
Id_boundry = I0 ./ (1-D); %average input current at boundry  :: THis is
assuming 100% efficient ideal system
Id_fullLoad = I0_max ./ (1-D); %average input current at max load
deltaI = (Vd * D ) / (L * Fsw);
Id_fullLoad_max = Id_fullLoad + deltaI / 2;
Id_fullLoad_min = Id_fullLoad - deltaI / 2;

C = V0 * D * Tsw / (R_max * deltaV);
```


C. Torroid calculation Testing 287 highflux

```
outter = 0.058; %mm convert to m
inner  = 0.0255;
z      = 0.0162;
%L      = 126.7e-6; %253.4uH needed
L = 253e-6; %L = 335.7e-6; %335.7uH needed
%L = L/2;
R = (outter+inner)/4;
A = ((outter-inner)/2)*z;

u0 = (4*pi)*10^(-7);
ur = 125;
N = sqrt((L*2*pi*R) / (u0*ur*A)) % Can find the no of turns

Bsat = 1.5; %Tesla
Isat = (Bsat*2*pi*R) / (u0*ur*N) % Make sure inductor current is less than
this. else it will saturate.

%Finding using AL value
Al = 287e-9;
N_direct = sqrt(L/Al)
```

```
Isat_direct = Bsat*A/(N_direct*Al)
```

D. Heat sink calculations

```
Rca = 3.6;
Ta = 26;
%Boost
Rjc = 0.32;
Rja = Rjc + Rca;
P = 18.5;   %Power in Boost MOSFET
Tj_boost = Rja * P + Ta;

%H bridge
Rjc = 2;
Rja = Rjc + Rca;
P_L = 1.5671;   %Power in lowside MOSFET
P_H = 1.3693;   %Power in highside MOSFET
Tj_L = Rja * P_L + Ta;
Tj_H = Rja * P_H + Ta;
```

E. MOSFET related losses

```
Vin = 12;
Iout = 2;
Vout = 100;
d = 0.88;
%Let us assume it's 100% efficient and take a close approximation for the
%inductor current
Iin = Vout*Iout/Vin;
Vds = Vout;
Ids = Iin;
Ron25 = 0.072;
Ron150 = 0.19;
tr= 18e-9;
tf= 6e-9;
fsw = 45e3;
Psw_boost = Vds*Ids*fsw*(tf+tr)/2
Pcon_boost25 = (Ids^2)*Ron25*d
Pcon_boost150 = (Ids^2)*Ron150*d
Pin = Vin*Iin;
p_boost25 = Psw_boost +  Pcon_boost25
p_boost150 = Psw_boost +  Pcon_boost150

effi_boost25 = (Pin - p_boost25)*100 / Pin
effi_boost150 = (Pin - p_boost150)*100 / Pin

%Hbridge
Iload = 2;
Vds = Vout;
Ids = Iload;
Ron25 = 0.54;
Ron150 = 1.4;
tr= 9e-9;
tf= 13e-9;
sinefreq = 50; %50 Hz
Davg = 0.633833948; % sum of all Ds / no of Ds -- done using excel

Psw_invL = (Vds*Ids*fsw*(tf+tr)/2)*2  % For 2 low side switches
Psw_invH = (Vds*Ids*sinefreq*(tf+tr)/2)*2  % the square wave is 50Hz
```

```
Pc_inv25 = (Iload^2)* Ron25 * Davg  % no need to *by 2 since 1 is on half of the time only
Pc_inv150 = (Iload^2)* Ron150 * Davg

P_inv_Lside_one_MOSFET = Pc_inv25 + Psw_invL;
P_inv_Hside_one_MOSFET = Pc_inv25 + Psw_invH;
Psw_inv = Psw_invL + Psw_invH;
Pinv25  = Psw_inv + Pc_inv25;
Pinv150  =  Psw_invL + Psw_invH + Pc_inv150;

% Total power desipation
Ptot25 = p_boost25 + Pinv25
Ptot150 = p_boost150 + Pinv150
systemEff25 =  (Pin - Ptot25)*100 / Pin
systemEff150 =  (Pin - Ptot150)*100 / Pin


%power after tri state;
loss25 = 1.3949;
loss150 = 3.0438;

systemEff25_tri =  (Pin - Ptot25 - loss25)*100 / Pin
systemEff150_tri =  (Pin - Ptot150 - loss150)*100 / Pin

%efficiency drop due to tri state
systemEff25 - systemEff25_tri
systemEff150 - systemEff150_tri
```

F. Snubber Calculations


```
%C Calculations
clear all;
clc;
Vdc = 325.26;
Iload = 2;
Toff = 13e-9;  % chk the time 80+13 ?
fsw = 45e3;
C = Iload* Toff / Vdc  % ans = 68pF


%R Calculations
Irep_peak = 18; % Pulsed Drain Current
Iload_max = 2;
ip = Irep_peak - Iload_max;
Rmin = Vdc/ip

Ton_min = 9 ; % chk the time 9 + 12
R_max = Ton_min / (5*C)

R_wattage = C*(Vdc^2)*fsw /2


%L Calculations
di_by_dt_limit = 2/(9e-9); % during MOSFET turn on = iload / trise
L_min = Vdc/di_by_dt_limit

%R1 Calculations
%R1_min = 5*L_min/Toff
R1_min = 5*L_min/22e-8  % 1%duty cycle is taken as the toff

Vrep_peak = 650; % this is the drain source breakdown voltage
```

```
R1_max = (Vrep_peak - Vdc)/Iload_max

R1_wattage = L_min * Iload_max^2 * fsw /2
```

G. Modeling the Plant

```
Vin = 12;  % input voltage
D = 0.88;  % Stady state duty ratio
L = 253e-6;% Inductor
C = 220e-6;% Capacitor
R = 50;  %Make R low to show the RHPZ effect

%Steady State Model of the ideal Boost Converter(Plant) given by
As,Bs,Cs,Ds
As = [0 -(1-D)/L; (1-D)/C -1/(R*C)];
Bs = [1/L 0 0; 0 -1/C 0]; % the d input is zero
Cs = [0 1; 1 0];
Ds = [0 0 0; 0 0 0]; % Bs and Ds should be the same dimentions.

Vo = -Cs(1,:) * inv(As) * Bs(:,1).*Vin; % Steady State Output Voltage


Ig = -Cs(2,:) * inv(As) * Bs(:,1).*Vin; % Steady State Input Current


%Small signal model of Boost Converter

a = [0 -(1-D)/L; (1-D)/C -1/(R*C)];
b = [1/L 0 Vo/L; 0 -1/C -Ig/C];  % Steady state values Vo,Ig values are
needed.
%c = [0 1; 1 0];
c = [0 1]; % We r only interested in Vo
d = [0 0 0]; %b & d dimentions should match

ulabels = ['Vin Iz d'];
ylabels = ['Vo Ig'];
xlabels = ['Il Vc'];

disp('The Steady State model');
printsys(As,Bs,Cs,Ds,ulabels,ylabels,xlabels);  %Prints the Steady State
model of the system
disp('The Small Signal model');
printsys(a,b,c,d,ulabels,ylabels,xlabels); %Prints the Small Signal model
of the system

disp('Transfer Function in S Domain');
disp('Vo/d (s)');
sys = tf(ss(a,b(:,3),c,[0])); %Tr fn Vo/d
[np, dp] = ss2tf(a,b(:,3),c,[0]);  %Tr fn Vo/d
tfBoostVo_d = zpk(tf(ss(a,b(:,3),c,[0]))); % Tr fn in Zero pole gain form

test = pzplot(sys);
pause;

Ts = 10e-6; %Sampling Time

sysd = c2d(sys,Ts,'zoh');
step(sys,'-',sysd,'--');
pause;
```

H. Modeling the Controller

```
%Define the controller structure---This is a PI controller
zero_c = 3000;
nc = [1 zero_c];  % numerator controller
dc = [1 0];      % dinominator controller

%Define the transfer function H
nh = [1];
dh = [1];

%Loop transfer function  Gc.Gp.H
nl = conv(conv(nc,np),nh);
dl = conv(conv(dc,dp),dh);
loopTF = tf(nl,dl);

%Transfer Function in Zero Pole Gain form
loopTF_ZPK = zpk(loopTF) % will be a third order system rlocus(loopTF)
% We have to select a suitable gain 'k' from the LHS of this plot
pause;

Ts = 10e-6; %Sampling Time

%Let's take k =0.104 The closed loop system will be:
%k =1.02e-5; %k = kp
k = 7.32e-6;

% Controller tr fn  with gain k
ControllerTF = tf(nc*k,dc);
%Converting PI controller from continuous- to discrete-time
Controllerd = c2d(ControllerTF,Ts,'zoh');

% Close loop tr fn with gain k
[n d] = feedback(conv(nc,np)*k,conv(dc,dp),nh,dh);
kp = k;
ki = zero_c * k;
closedSys = tf(n,d);

%Converting Closed loop system from continuous- to discrete-time
closedSysd = c2d(closedSys,Ts,'zoh');
step(closedSys,'-',closedSysd,'--');
%step(tf(n,d)); %step responce with the desired gain k
pause;

bode(tf(n,d)); grid on; % Gain and Phase of the Closed loop system
pause;
close;
```


I. Tri-State boost converter

```
Vin = 12;             % input voltage
Vo = 81.25;           % output voltage

L = 253e-6;           % Inductor
C = 220e-6;           % Capacitor
R = 50;               % Load resistance
f = 45e3;
T = 1/f;

Ilavg = (Vo^2)/(Vin*R);
```

```
Ildelta = Vin*T/L*(1-Vin/Vo);
Ic = Ilavg - Ildelta/2;
Iref_max = Ilavg + Ildelta/2;

Db = L*(Iref_max - Ic)/(T*Vin);      % Boost duty cycle
Do = Db/(Vo/Vin - 1);                % Cap charge duty cycle
% Db, Do is reduced by 10% to introduce Df, without changing Boost
gain.
Df_tri = Db*0.1 + Do*0.1;
Db_tri = Db*0.9;
Do_tri = Do*0.9;

Vo_tri = Vin*(Db_tri + Do_tri)/Do_tri;  % Gain unchanged
% The Iref_max will not get affected with the duty cycle change.
% (The diL/dt will be higher than in the classical case)
% However, Iref_min will be higher because of the introduction of
Df.
Iref_min = Iref_max - Do_tri*T*(Vo-Vin)/L;
k1 = Iref_min - Ic;
%Freewheeling current -> Idc
Io = Vin*Ilavg/Vo;
Idc = Io/Do_tri - (Vo-Vin)/(2*L)*Do_tri*T;
%Steady State Model of the ideal Tri-state Boost Converter
As = [0 -Do_tri/L; Do_tri/C -1/(R*C)];
Bs = [(Db_tri + Do_tri)/L; 0 ];
Cs = [1 0; 0 1];         %Output matrix
Ds = [0 ; 0]; % Bs and Ds should be the same dimensions.

Ig = -Cs(1,:) * inv(As) * Bs(:,1).*Vin; %Steady State Input Current

Vo = -Cs(2,:) * inv(As) * Bs(:,1).*Vin; %Steady State Output voltage


%Small signal model of Tri State Boost Converter
a = [0 -Do_tri/L; Do_tri/C -1/(R*C)];
b = [Vin/L  -(Vo-Vin)/L (Db_tri + Do_tri)/L; 0 Ig/C 0];  % Steady
state values Vo,Ig values are needed.
cv = [0 1]; % We r only interested in Vo
d = [0 0 0]; %b & d dimentions should match
ci = [1 0];% Now we are only interested in IL.

disp('Il/db(s)');
G11 = tf(ss(a,b(:,1),ci,[0])) %Tr fn Il/db
[n_i, d_i] = ss2tf(a,b(:,1),ci,[0]) %Tr fn Il/db
G11_zpk = zpk(G11)

disp('Il/do (s)');
G12 = tf(ss(a,b(:,2),ci,[0])) %Tr fn Il/do
G12_zpk = zpk(G12)

disp('Il/vin (s)');
F1 = tf(ss(a,b(:,3),ci,[0])) %Tr fn Il/vin

disp('Vo/db (s)');
G21 = tf(ss(a,b(:,1),cv,[0])) %Tr fn Vo/db
```

```
[n_v, d_v] = ss2tf(a,b(:,1),cv,[0]) %Tr fn Vo/db
G21_zpk = zpk(G21)

disp('Vo/do (s)');
G22 = tf(ss(a,b(:,2),cv,[0])) %Tr fn Vo/do

disp('Vo/vin (s)');
F2 = tf(ss(a,b(:,3),cv,[0])) %Tr fn Vo/vin

disp('Vo/iL (s)');
sys = tf(n_v,n_i)  %Tr fn Vo/iL
```

Finding k_1, k_2, k_3 in the third state

For the third state to begin, the Boost period should be over, and after that when the inductor current I_L is falling from i_{ref}^{+} to i_C, the third state could be introduced. For this experiment $i_{ref}^{-}$was selected as the mid-point of the current ripple, and two reference voltages 81.25V, 84V were taken as test cases. For the two cases the inductor current midpoints were measured as 13.695A and 14.635A respectively from the Matlab Simulink simulation. From equation 4.4,

Case 1: $13.695 = k_1 + 81.25k_2 - 12k_3$

Case 2: $14.635 = k_1 + 84k_2 - 12k_3$

By the above k_2 can be found as 0.3418. Also for the capacitor charge state and the freewheeling state to exist,

$$0 < k_1 < 0.73$$

should satisfy. So, k_1 was selected as 0.5, and k_3 could be calculated as 1.2147.