IEEE Masterclass – DC – DC Converters

Sumukh Surya, ECS 2

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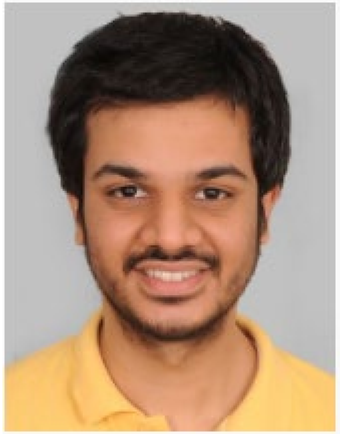
About Presenter



Sumukh Surya completed Masters in Power Electronics and Drives from Manipal Institute of Technology and is currently working as a Senior Engineer at Bosch Global Software Technologies Private Limited (BGSW), Bangalore. He works on power converters and battery algorithms. He has six years of experience in automotive domain and his research areas include mathematical modeling of DC - DC converters and development of Battery Management Systems (BMS) algorithms.

Google Scholar – https://scholar.google.com/citations?user=rexgwGUAAAAJ&hl=en&oi=ao

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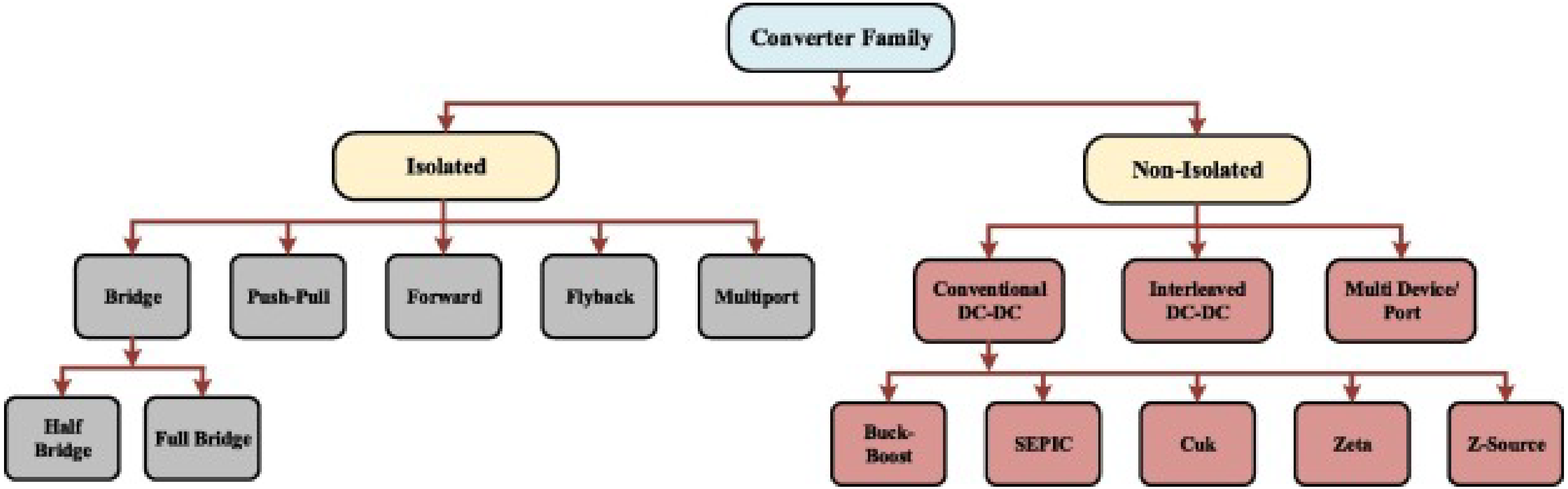
Contents

Introduction to DC – DC Converters

- Converters are used to transform power from one form to another form
- Applications: Electric Vehicles (EV), Consumer electronics, LED driver etc;
- These regulate the voltage levels using electronic switching device
- Differences between Regulator and DC – DC converter

Parameters	DC - DC converters (switching regulators)	LDO regulators (linear regulators)
Efficiency	High	Low
Price	High	Low
EMI	High	Low
Design	Difficult	Easy
Components	Many	Few
Load Current	Large	Small

Introduction to DC – DC Converters



- All DC – DC converters shall obey the principles of volt-sec (L) and amp-sec (C) for efficient energy conversion
- Inductors and capacitors are designed assuming current and voltage ripples

Principle of Volt - Sec and Amp – Sec Balance

- This ensures inductor and capacitor are charged and discharged at equal intervals to avoid saturation

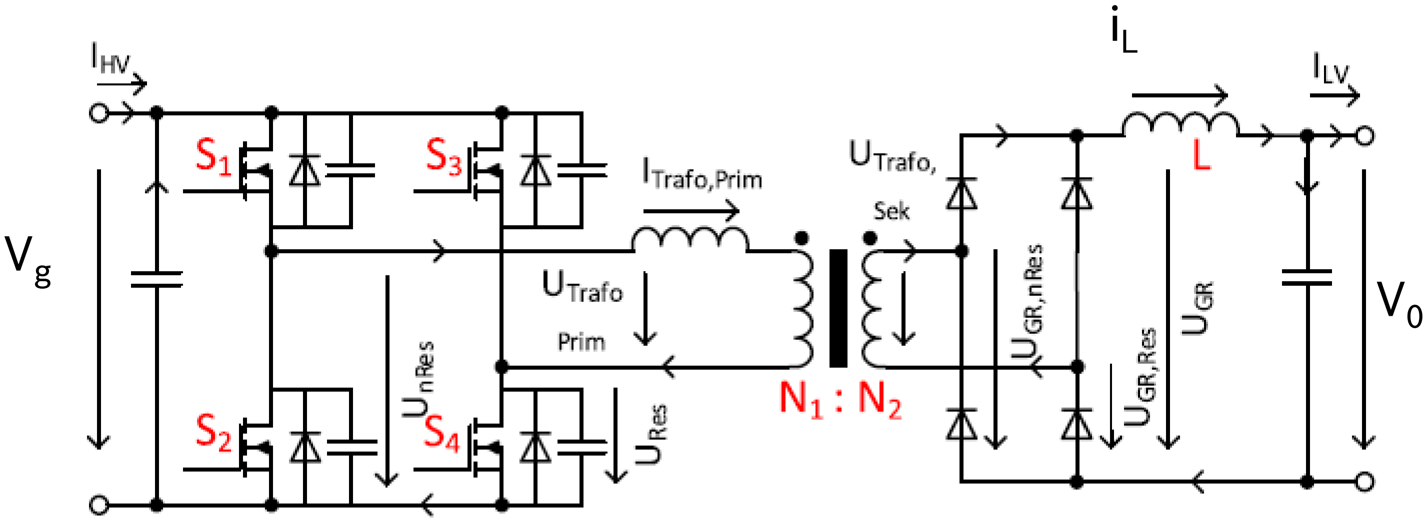
$$Voltage\ X\ Second = Flux$$

$$Ampere\ X\ Second = Voltage$$

- Typical converters used in EVs – Flyback, Phase Shifted Full Bridge(PSFB), Active Clamped Flyback (ACF) etc;

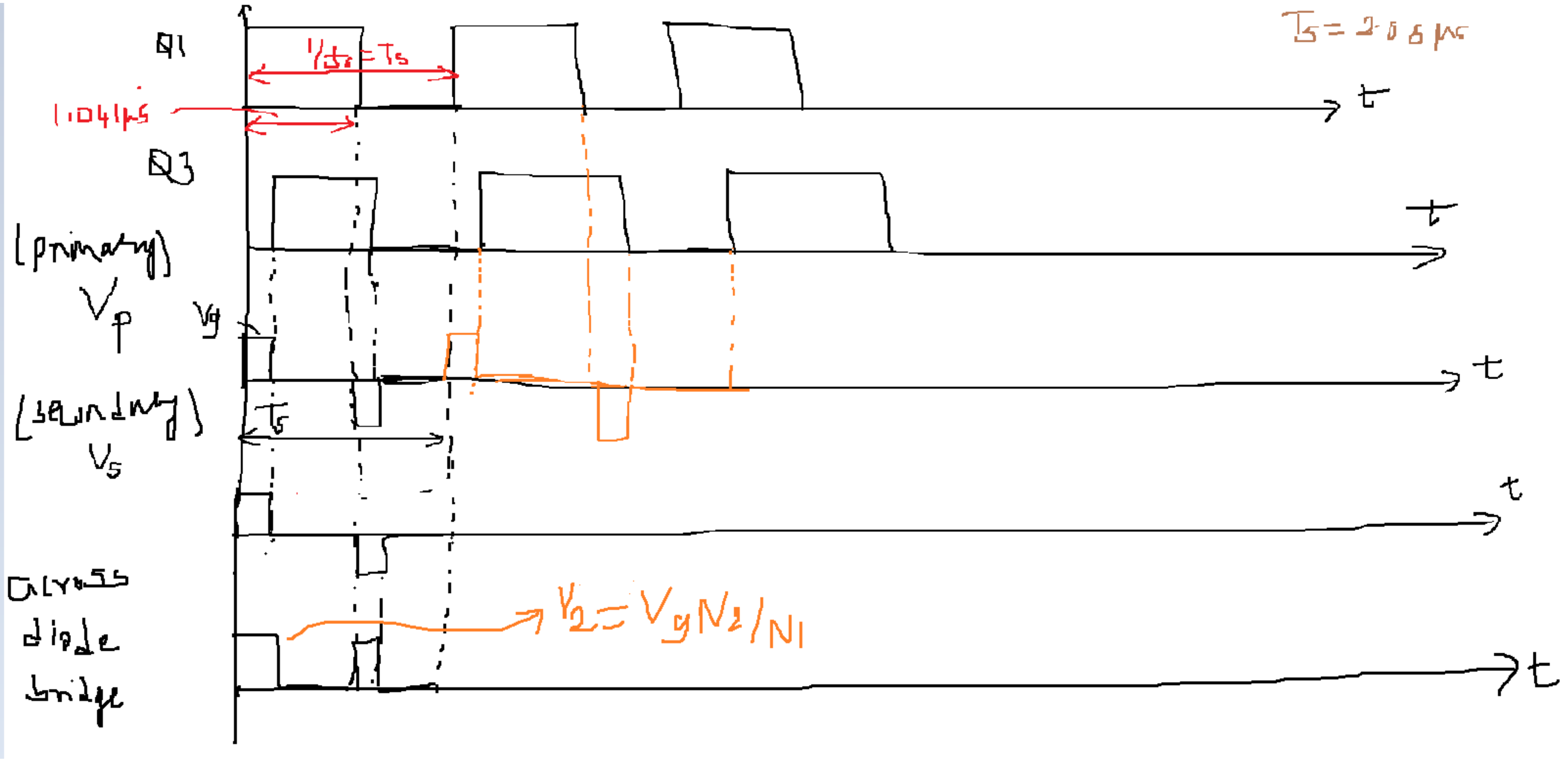
Why PSFB

- High efficiency
- Isolation between input and output
- Simple design – Similar to buck converter
- High efficiency as Zero Voltage Switching (ZVS) is possible
- High stability



Schematic of PSFB

Switching Sequence



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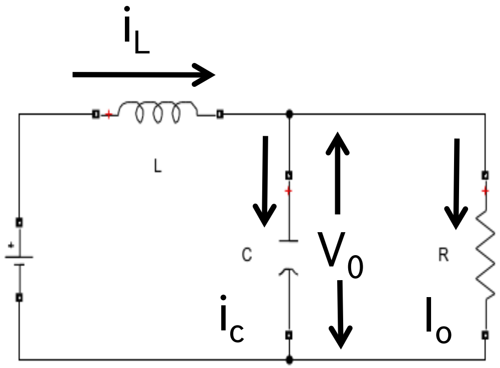
Small Signal Model – AC Modeling

- Across the secondary winding of the transformer, a pulsating DC waveform is observed. Hence, the equivalent circuit is like a buck converter

- Hence, the volt-sec and amp-sec balance equations are shown below



- During DT_s,

$$V_L = L\frac{di_L}{dt} = V_g - V_0 = V_g \frac{N_2}{N_1} - V_0 \qquad (1)$$

$$i_c = C\frac{dv_c}{dt} = i_L - \frac{V_0}{R} \qquad (2)$$

- During $(1\text{-}D)T_s$,

$$V_L = L\frac{di_L}{dt} = -V_0 \qquad (3)$$

$$i_c = C\frac{dv_c}{dt} = i_L - \frac{V_0}{R} \qquad (4)$$

Operating Points

SL.NO	Specifications	Value
1	Input Voltage, V_g	800 V
2	Output Voltage, V_0	14 V
3	Output Current, I0	160 A
4	Inductor, L	?
5	Capacitor, C	?
6	Switching Frequency, f_s	480 kHz

- Assume D ~ 0.3 and calculate N_2/N_1

$$\frac{V_0}{V_g} = \frac{N_2}{N_1} * 2D$$

- Assume $\frac{\Delta i_L}{I_L} = 1\%$ $\frac{\Delta V_0}{V_o} = 1\%$ $R = \frac{V_0}{I_0}$ $I_L = \frac{V_0}{R}$

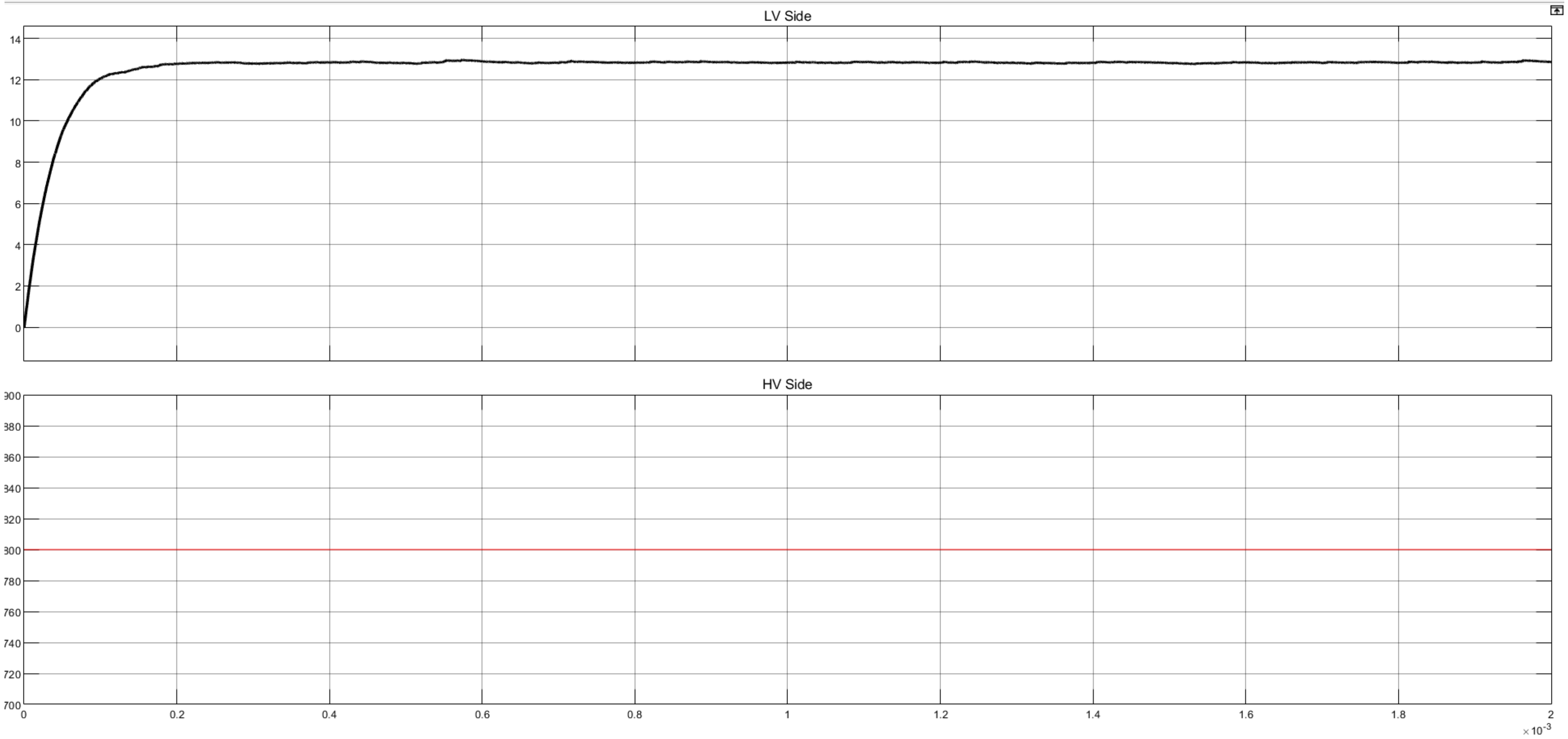
- Frequency of the voltage at the secondary is two times that of primary

$$L = \frac{(V_g * \frac{N_2}{N_1} - V_0) * 2D}{2 * f_s * \Delta i_L} \qquad C = \frac{(1-2D)}{8 * L * (2 * f_s)^2 \frac{\Delta V_0}{V_0}}$$

- To enable ZVS, duty cycle at the input side is fixed to 50 % and the turn on time varied

$$D = \frac{t_{on}}{T}$$

Results of Open Loop Simulation



Output Voltage Vs. Input Voltage for phase angle = 150 °

Small Signal Model – AC Modeling

- Method to obtain the transfer function of power converters

- Small magnitude changes at small frequencies are applied on the converter and the response is captured

- State Space Averaging technique is used to find the transfer function using state space matrices (A, B, C and E)

Need for Closed Loop

- Primary idea to find the transfer function is to establish a closed loop configuration and enable constant voltage operation under different conditions (change in V_g, load, parameters and ripples in V_g)

- This also helps in analyzing the stability of the open loop system using root locus and bode plot etc;

- To linearize the converter different control tools are used viz; (a) Small Signal Model (b) State Space Averaging and (c) Circuit Averaging State

- Space Averaging model is used for developing cascade control

Small Signal Model – AC Modeling

- Reducing (1), (2)..(4) to the state space form $\dot{X}$= AX + BU, Y = CX + DU,

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\underbrace{\begin{bmatrix}0 & -1/L\\ 1/C & 1/(RC)\end{bmatrix}}_{A_1}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\underbrace{\begin{bmatrix}\frac{N2}{N1*Vg}\\ 0\end{bmatrix}}_{B_1}[u]$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\underbrace{\begin{bmatrix}0 & -1/L\\ 1/C & 1/(RC)\end{bmatrix}}_{A_2}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\underbrace{\begin{bmatrix}0\\ 0\end{bmatrix}}_{B_2}[u]$$

$$\dot{X}=(A_1D + A_2(1-D))X + (B_1D + B_2(1-D))U=AX+BU \quad (3)$$

$$Y=(C_1D + C_2(1-D))X + (E_1D + E_2(1-D))U = CX+EU \quad (4)$$

(3) and (4) are called as the large signal models

Small Signal Model – AC Modeling

$$\dot{X} = (A_1 D + A_2(1 - D))\mathrm{X} + (B_1 D + B_2(1 - D)) = 0 \quad (5)$$

$$Y = (C_1 D + C_2(1 - D))\mathrm{X} + (E_1 D + E_2(1 - D)) = 0 \quad (6)$$

(5) and (6) represent the steady state behavior of the system

$$A = \begin{bmatrix} 0 & -\frac{1}{L} \\ 1/C & \frac{1}{RC} \end{bmatrix}; \mathrm{B} = \begin{bmatrix} \frac{N_1 V_g}{N_2 * L} \\ 0 \end{bmatrix}; C = [0\ 1]; E = [0] \quad (7)$$

$$A = \begin{bmatrix} 0 & -\frac{1}{L} \\ 1/C & \frac{1}{RC} \end{bmatrix}; \mathrm{B} = \begin{bmatrix} \frac{N_1 V_g}{N_2 * L} \\ 0 \end{bmatrix}; C = [1\ 0]; E = [0] \quad (8)$$

Small Signal Model – AC Modeling

- Once the final small signal state space model is developed, it can be further converted to Transfer Function using the standard formula $(C(SI - A)^{-1}B + E)$

- Where C is chosen based on V_0 or i_L

- $E = (A_1 - A_2)X + (B_1 - B_2)U$

Selection of Sensor Parameters

- Current sensor

$$R_f = \frac{3.3}{PeakValue}$$

- Voltage sensor

$$H = \frac{3.3}{PeakValue}$$

- Assume PWM gain, $V_m = 4$

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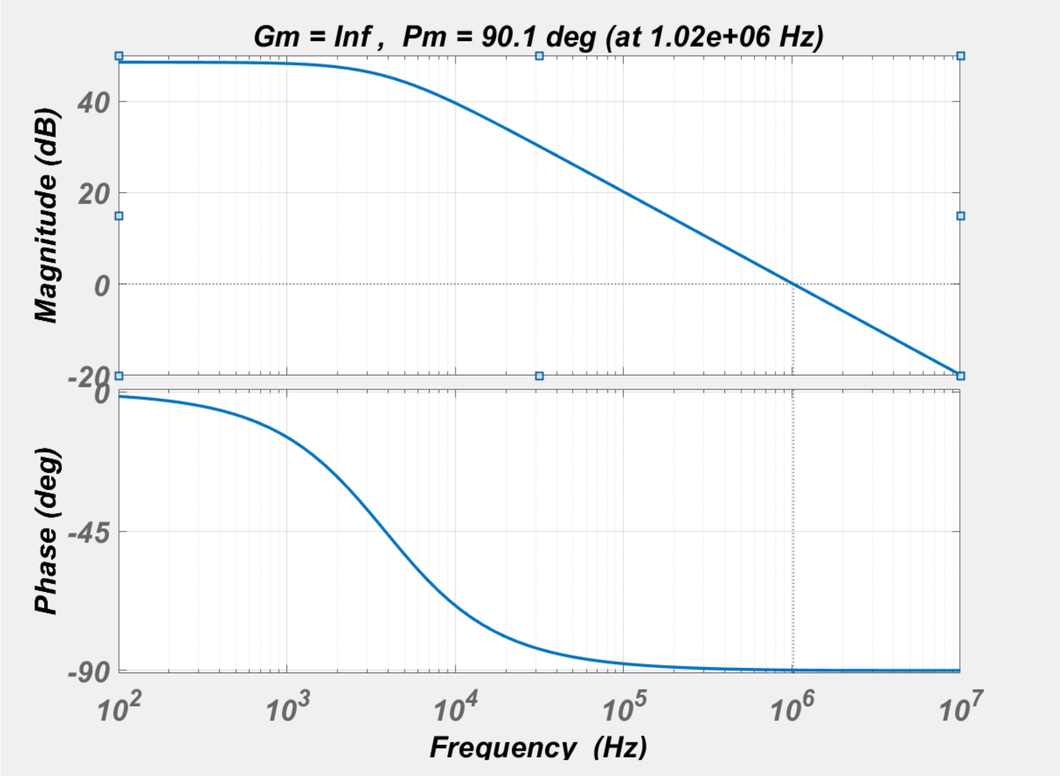
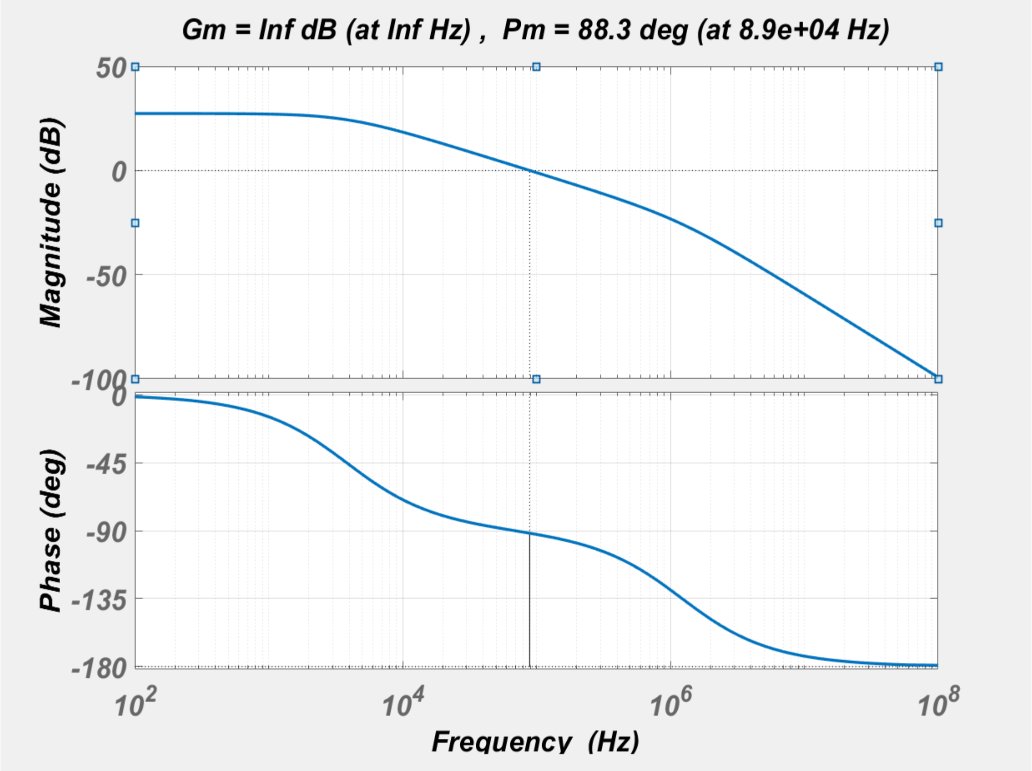
Small Signal Model – AC Modeling

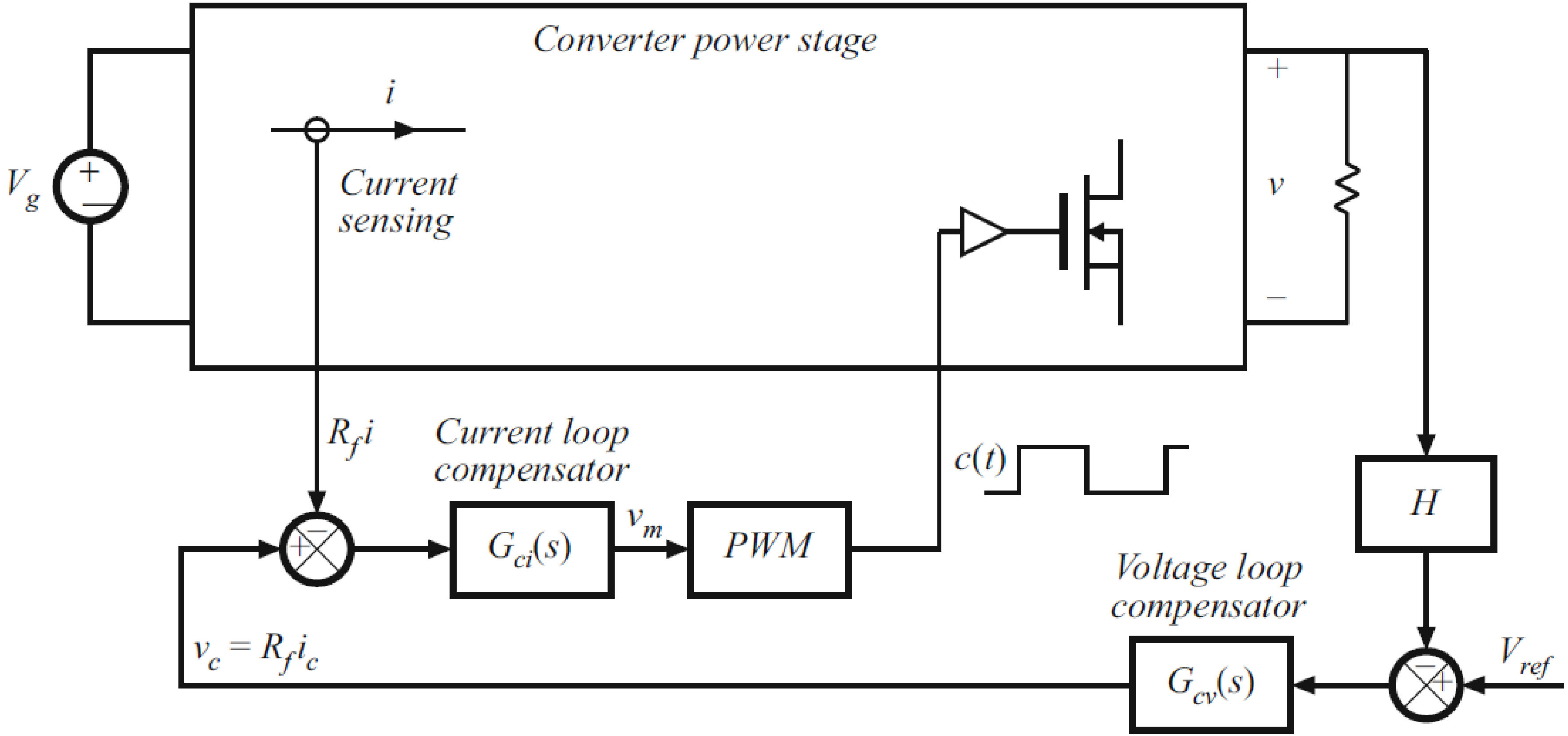


Frequency response of G_{id} – inductor current to duty cycle

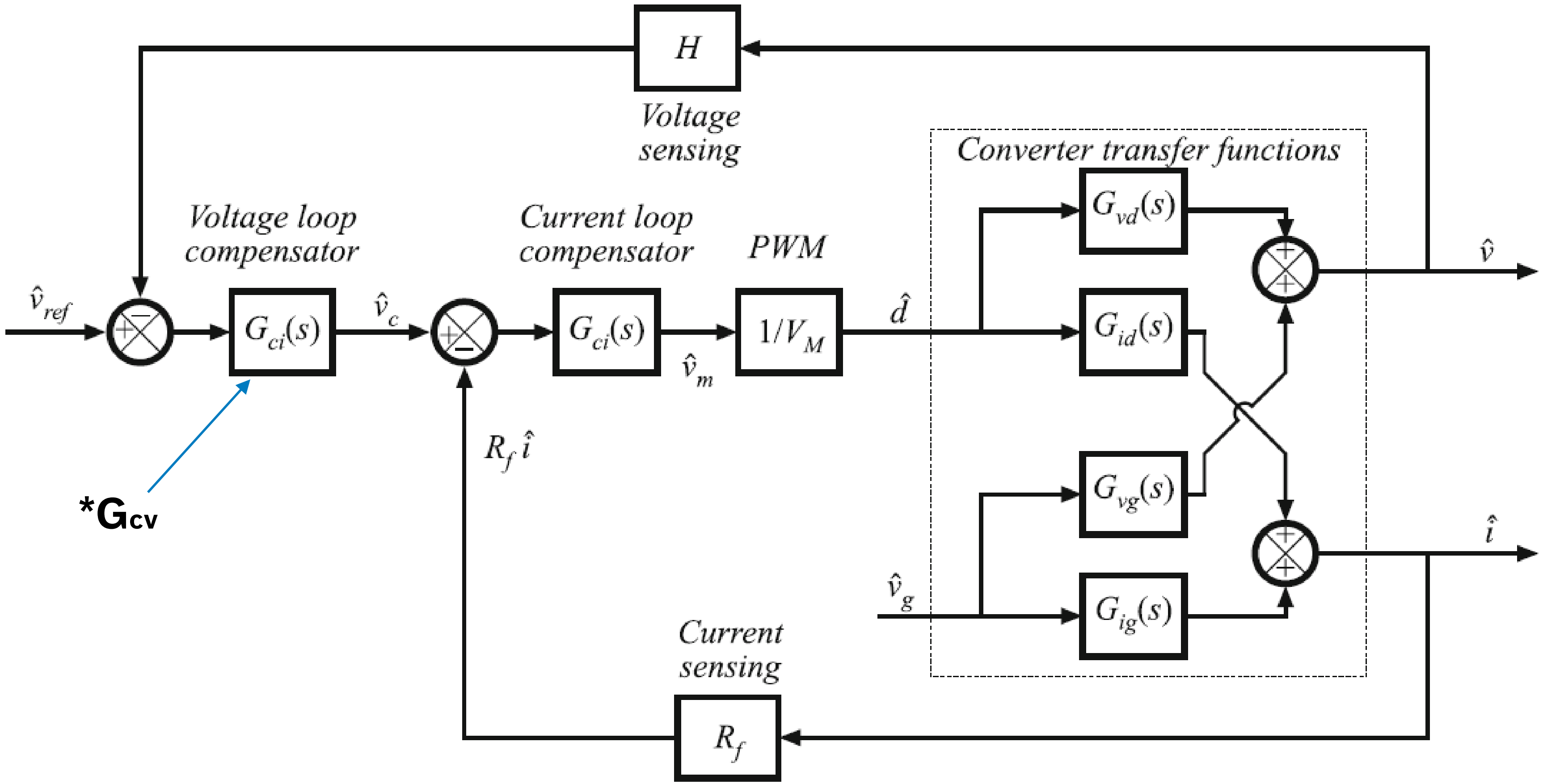


Frequency response of G_{vd} – output voltage to duty cycle

Block Diagram Representation of Double Loop Structure
General Representation



Block Diagram Representation of Double Loop Structure



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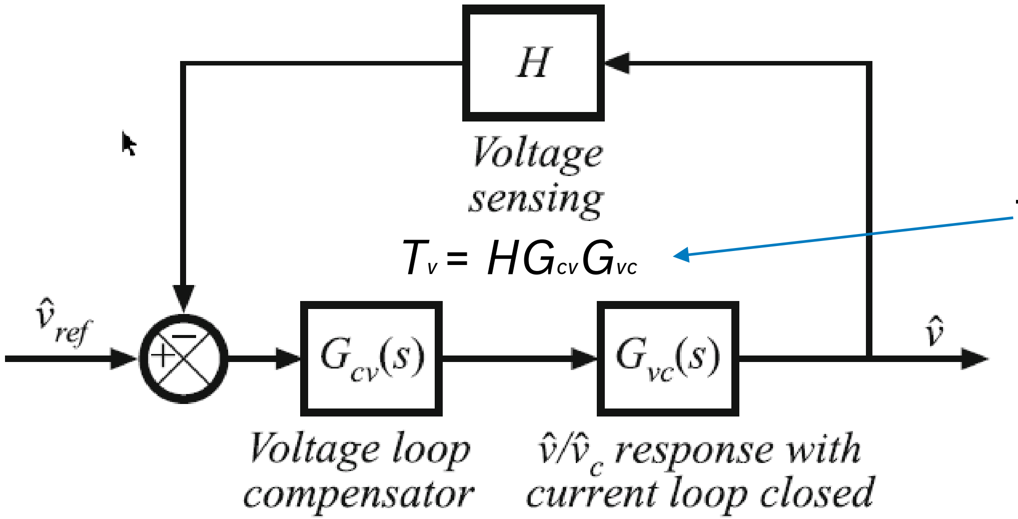
Defining Voltage Loop Gain

For the purposes of designing the voltage loop compensator, the system block diagram shown in the previous slide can now be simplified as shown



T_v is the Voltage Loop gain

Cascade Control Performance

➢ The best performance from DC – DC converter can be obtained

- ***When the current controller have a large bandwidth (cross-over frequency)***
- ***Voltage controller should behave like a 1^{st} order system***

➢ In PSFB, inductor current and output voltage behave likewise and hence, it is intended to design a cascade control

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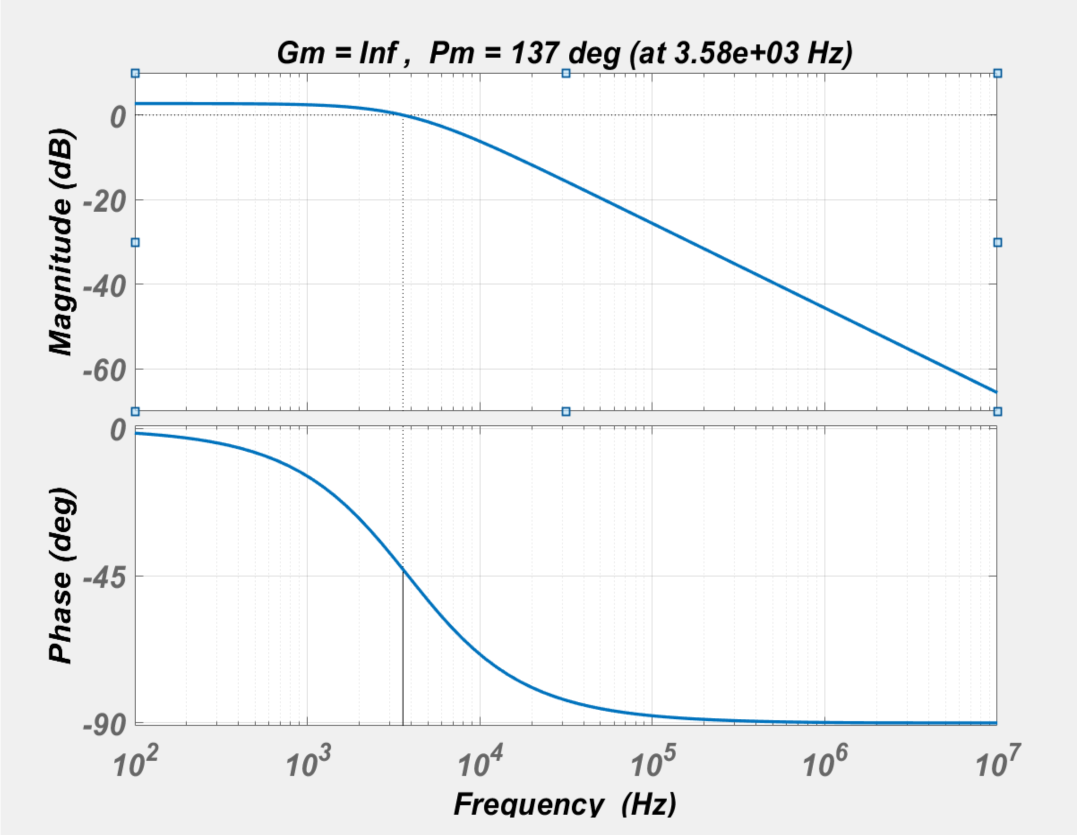
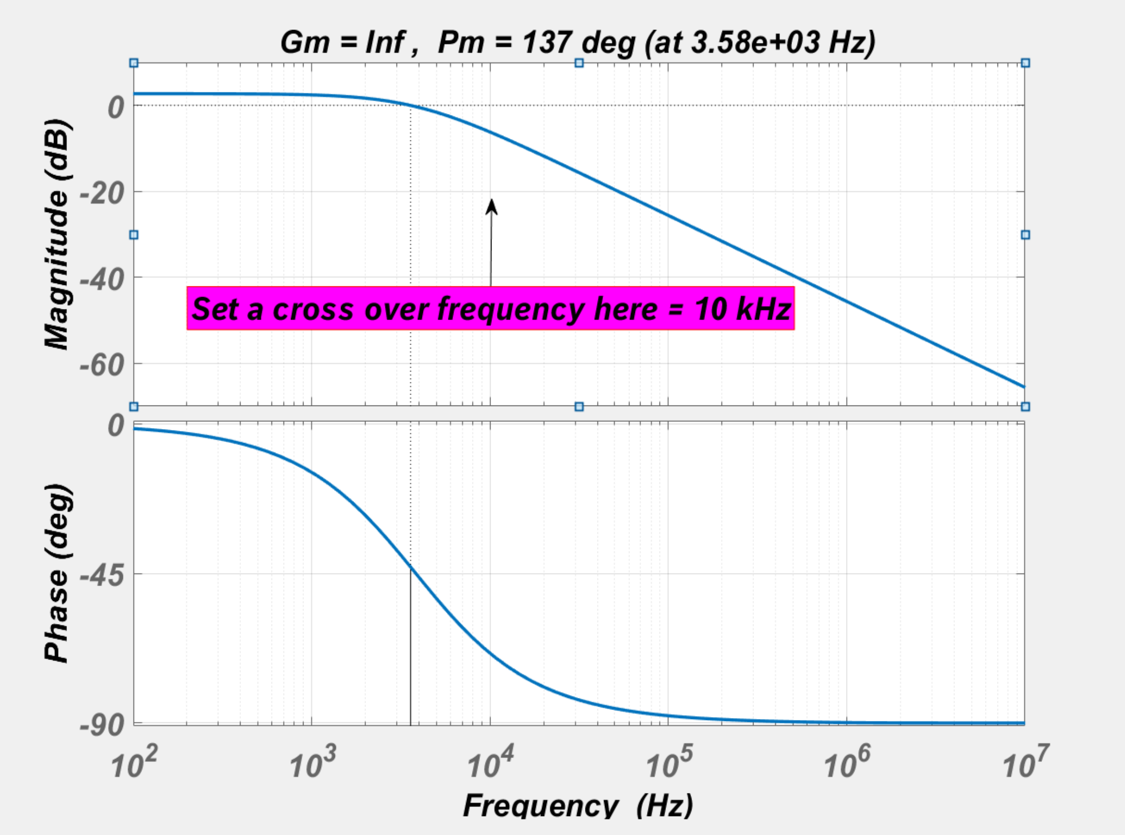
Average inductor current control - Inner Loop





Uncompensated Current Loop (G_{id} * R_f * 1/Vm)

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Average inductor current control - Inner Loop

- At 10 kHz, phase is -69.4° and phase margin is 180 - 69.4 = 110.6°

- For optimized overshoots and settling time, phase margin (PM) is ~ 45 to 70°

- Hence, a lag compensator / PI controller is required to reduce PM from 110.6 to 52°

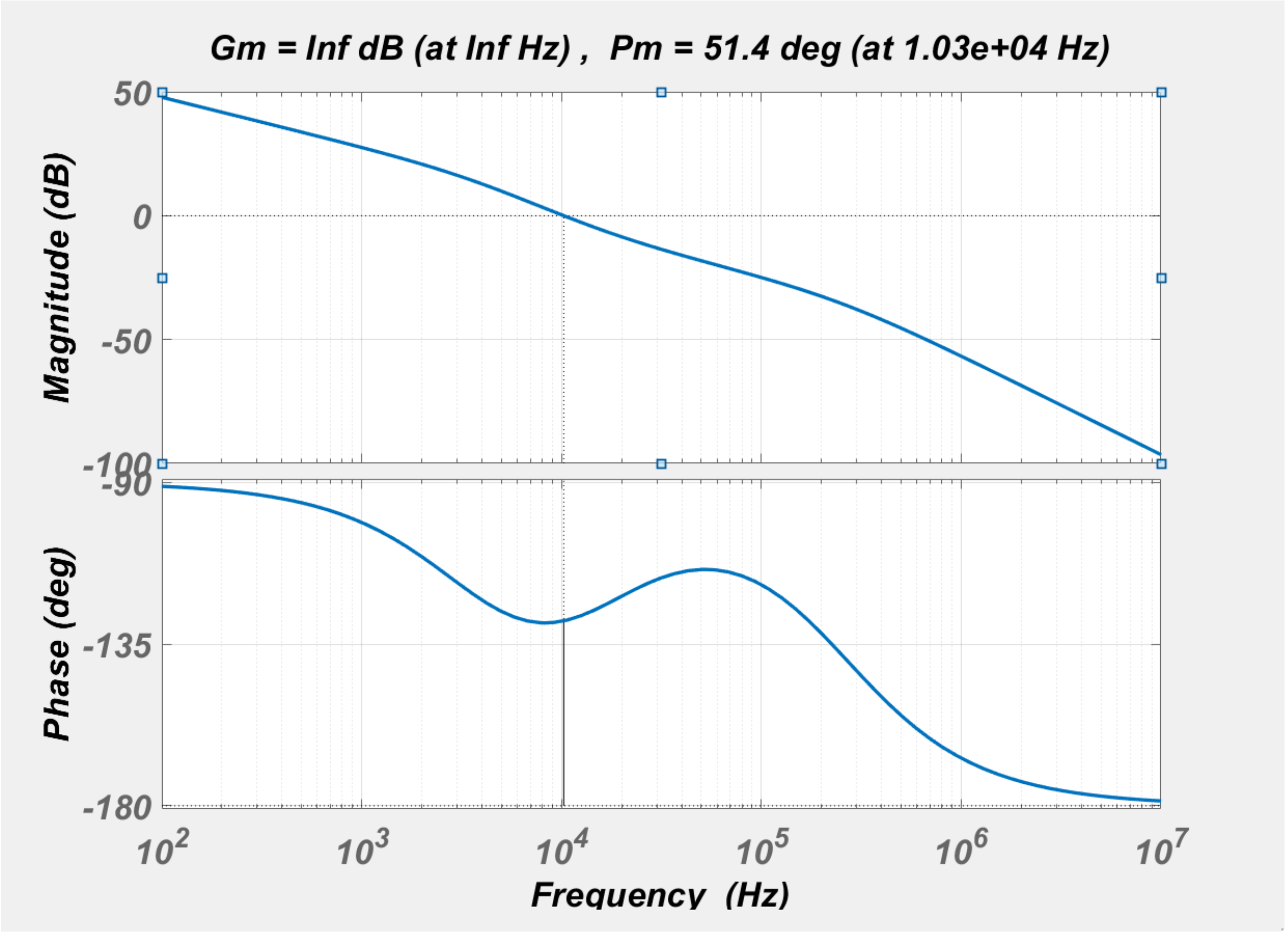
- PI controller $G_{PI} = K(1 + \frac{w_{Li}}{s})$

- Where $2 * pi * f_{L_i} = w_{L_i}$
- In addition, a high frequency pole is added to dimmish the ripples that occur from V_0 $I \alpha V$

- f_{Li} is accordingly chosen such that PM ~ 52°

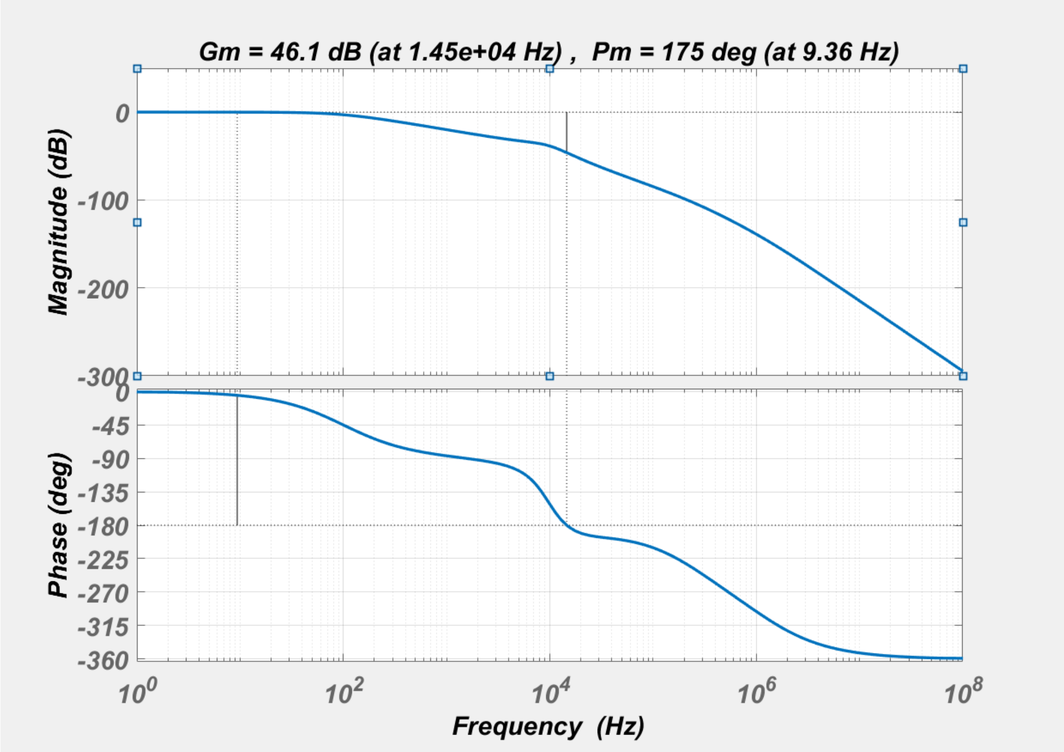
$$G_{PI} = \frac{K(1 + \frac{w_{Li}}{s})}{(\frac{s}{w_{p_i}} + 1)}$$

Average inductor current control - Inner Loop

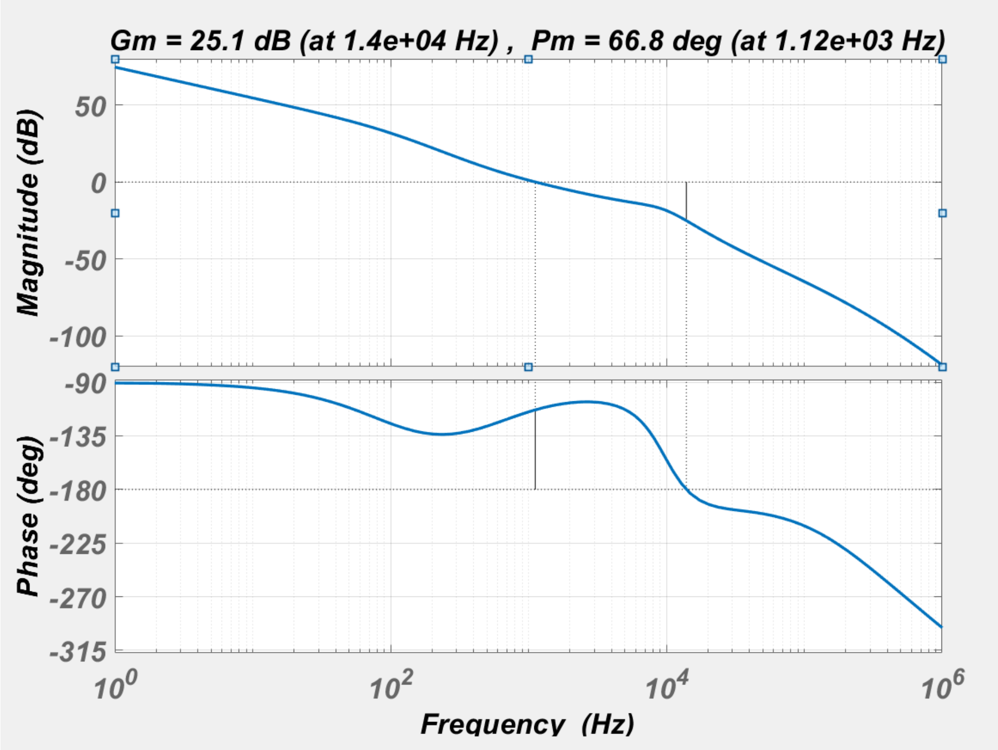


Compensated Current Loop (G_{id} * R_f * G_{ci}* $1/V_m$)

Average voltage control – Outer Loop

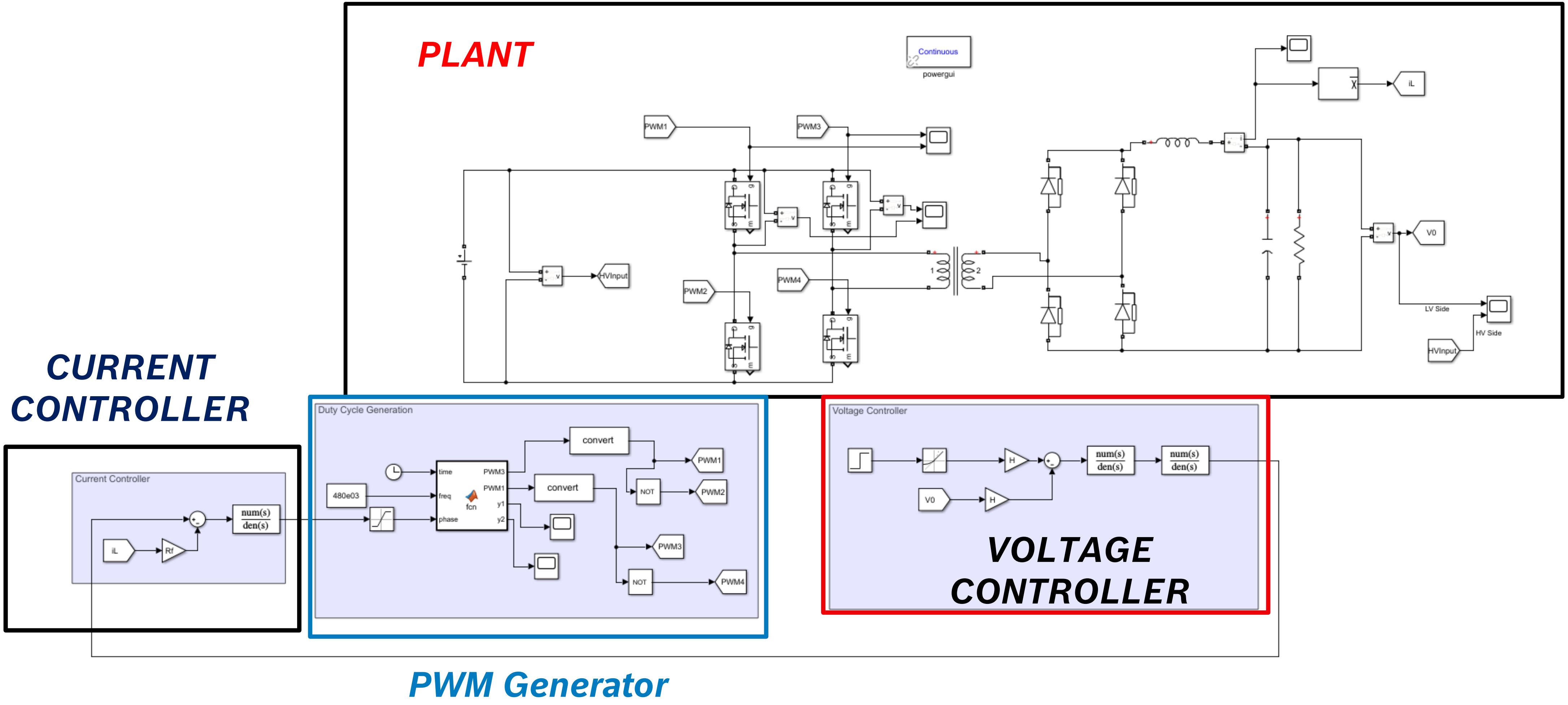


Uncompensated Voltage Loop

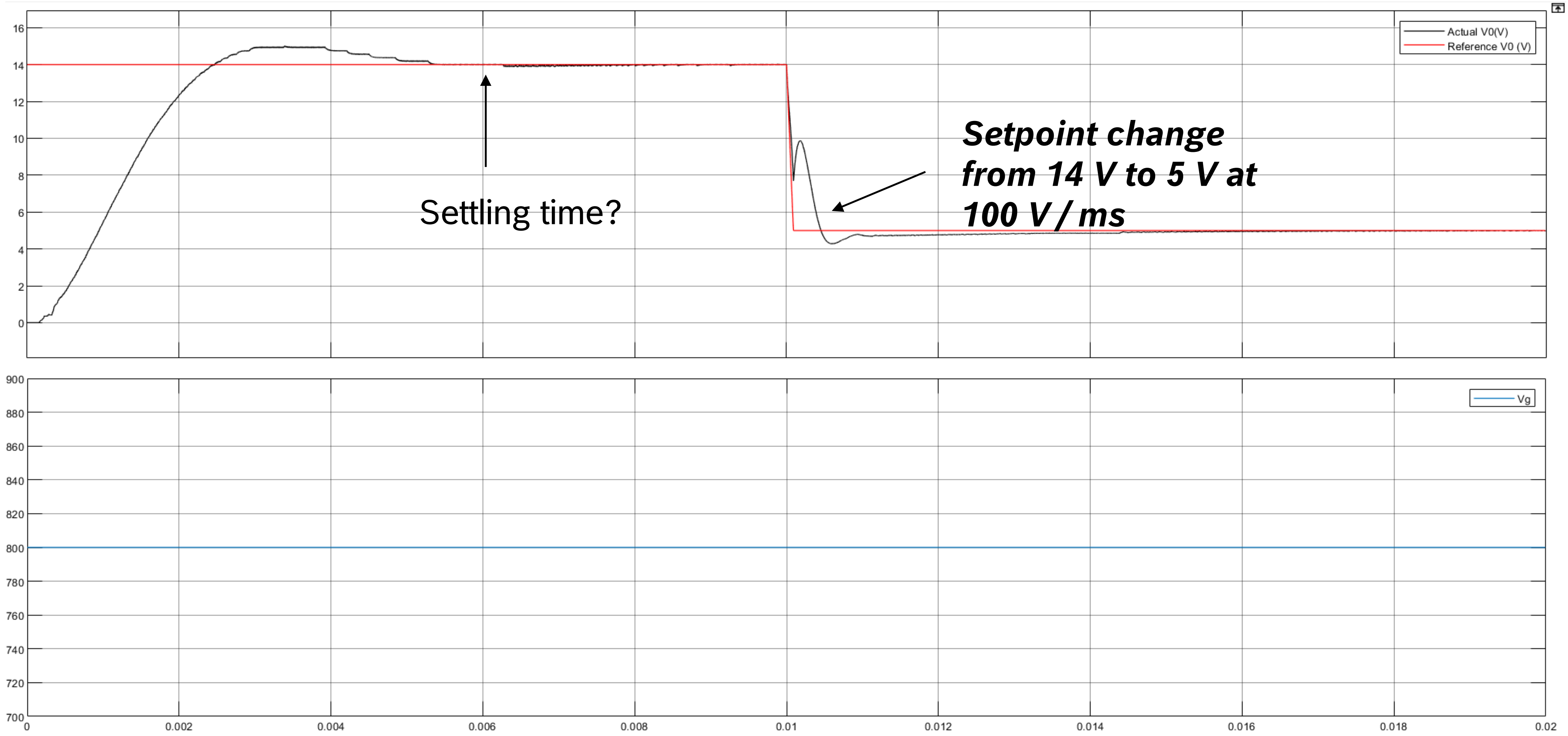


Compensated Voltage Loop

Results of Cascade Control



Results of Cascade Control



Various Tests

- Control for power converters in EV shall be tested based on

I. Load Test under high slopes – Deviation in output voltage shall be set by the customer

II. Ripple Test - Deviation in output voltage shall be set by the customer

III. Input Voltage variations - Deviation in output voltage shall be set by the customer

IV. LV set points – Settling time and overshoot shall be set by the customer

V. Parametric variations

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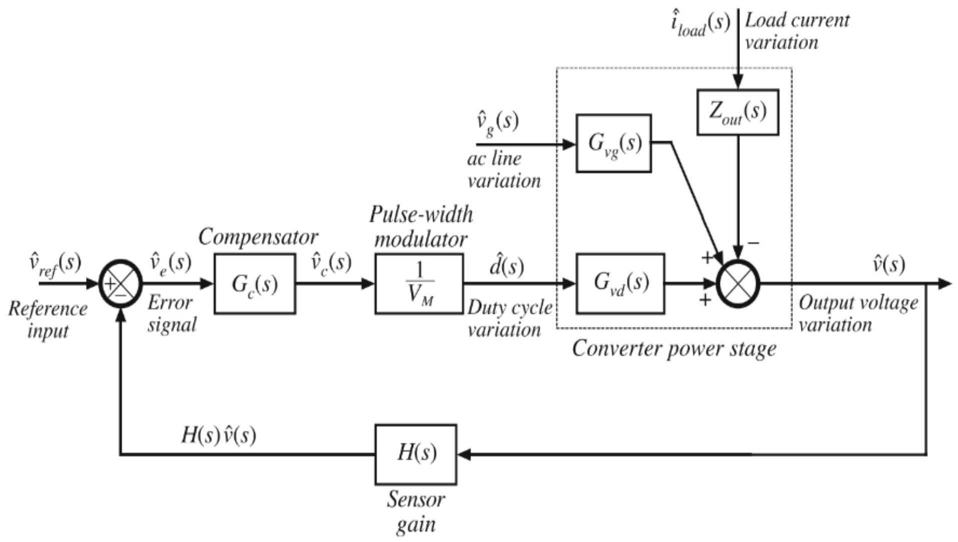
Assignment

- Design a PSFB in open loop for the specifications shown in slide 10 and observe the changes in the output voltage for different delay times (a) 45°, (b) 90 ° and (c) 180 °

- Design a single output voltage loop system based on the block diagram by choosing appropriate cross-over frequency



Hint – Bandwidth < (1/10) f_s

Assignment

- Settling time < 5 ms and overshoot < 200 mV for

(a) changes in the output voltage from 5V to 10 V at 100 V/ ms
(b) change in the load at 100 A / ms

- Inject HV side ripples of 15 V peak to peak upto 5kHz and LV peak to peak ripple < 150 mV

- Note: The above conditions shall be satisfied by choosing only ***one*** cross-over frequency

References

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THANK YOU

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