EE155/255 Green Electronics

Quiz Review
11/13/17

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STANFORD ENGINEERING

Course Logistics

- Quiz is Wednesday 11/15
  - 7:00PM to 9:00PM
  - Room ??
  - Covers all material to date
  - One page of notes allowed
- No Class on Wednesday
- Now in the project part of the course
  - Checkpoint 1 today – send the course staff an e-mail progress report – see Canvas
    - What you have accomplished
    - Any problems you encountered and how you dealt with them
    - Any revisions to your original plan
    - What you will do by Checkpoint 2
  - PCB review by checkpoint 2
  - Order parts and PCBs ASAP
  - Make use of your project mentors

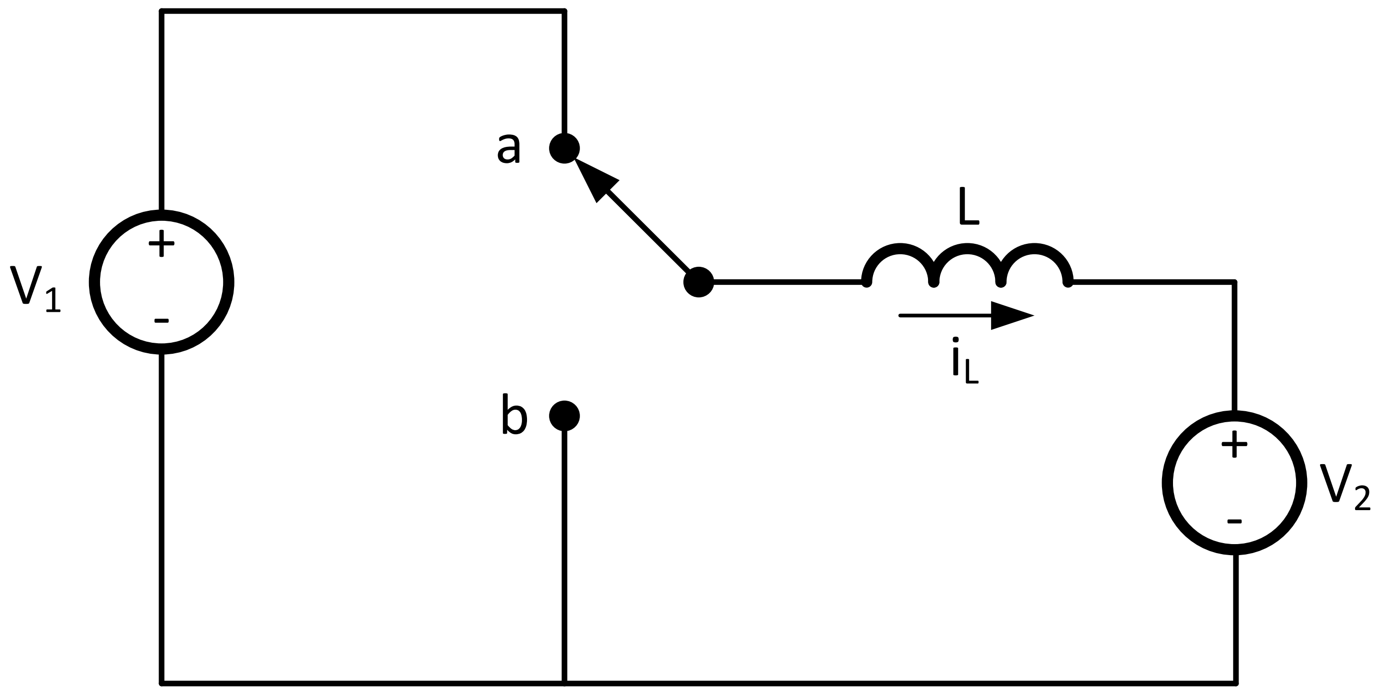
YAH

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Inverters, Grid, PF, and Batteries	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Thermal & EMI		6	P	6	Project	
14	11/8/17	Grounding, and Debugging						
15	11/13/17	Quiz Review				C1		
16	11/15/17	No Class						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Jon Wagner - Joby						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class				C4		
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

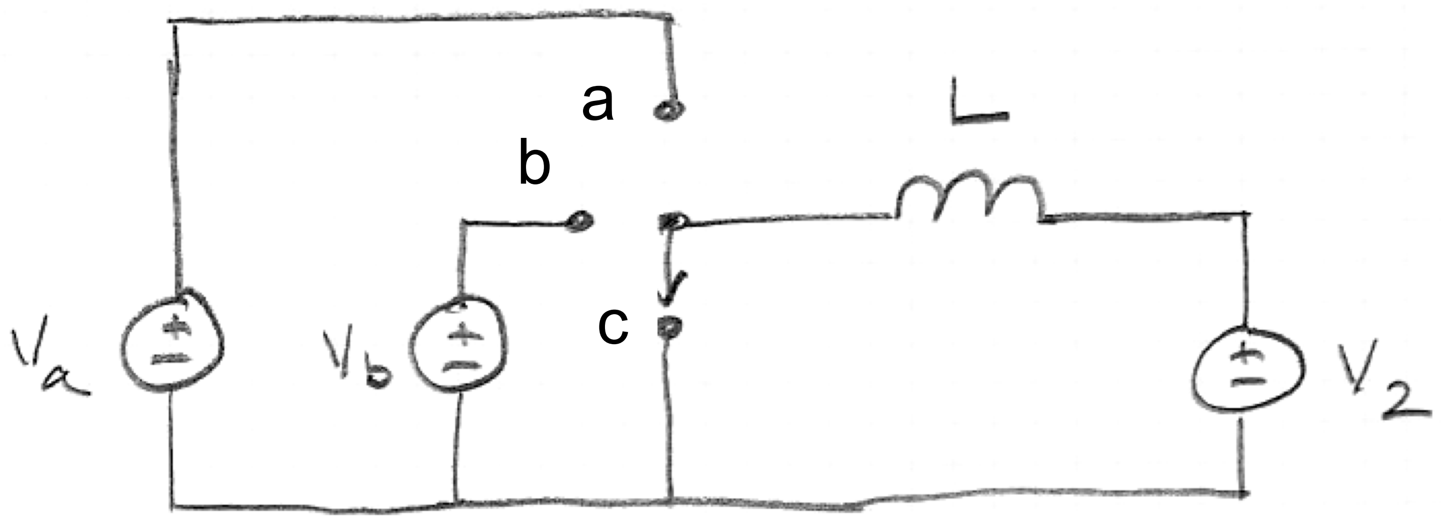
Quiz Review

Periodic Steady State

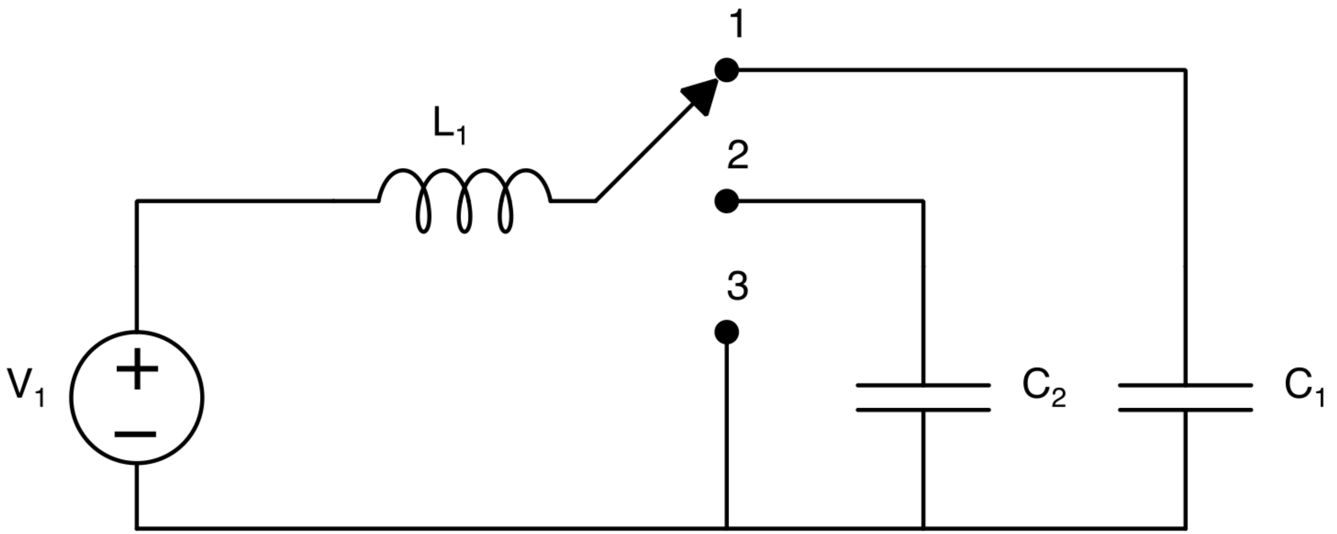
Buck Converter



Dual-Source Buck



Problem 1: Periodic Steady State Analysis [15 Points]



Consider the converter shown in the drawing above. The three-position switch operates with a cycle time of t_c = 10μs, has a duty factor in position 1 of D_1, a duty factor in position 2 of D_2, and a duty factor in position 3 of D_3. $D_1+D_2+D_3 = 1$. The inductor is 1μH and both capacitors are 100μF. Source V_1 is 1V. And in steady state, the voltage across C_2 is 2V.

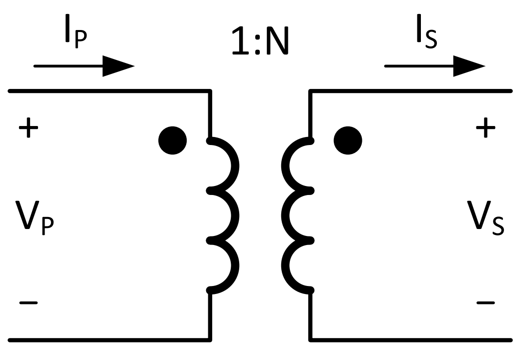
(a) [5 Points] If the converter is in periodic steady state, what is the voltage across the capacitor C_1? Give your answer in terms of the duty factors.

(b) [10 Points, 5 Points Each] Write expressions for the change in inductor current ΔI and the change in capacitor C_1 voltage ΔV over one cycle of the switch when not in the periodic steady state.

(c) [5 points] What is the natural frequency of the response on capacitor C_1 to a transient in duty factor.

Isolated Converters

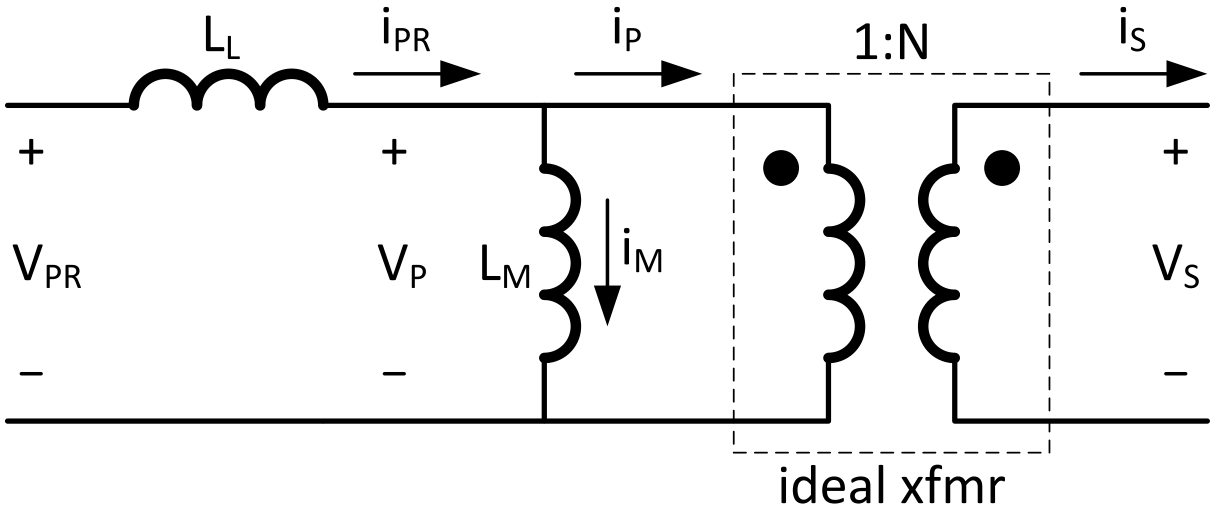
Ideal Transformer



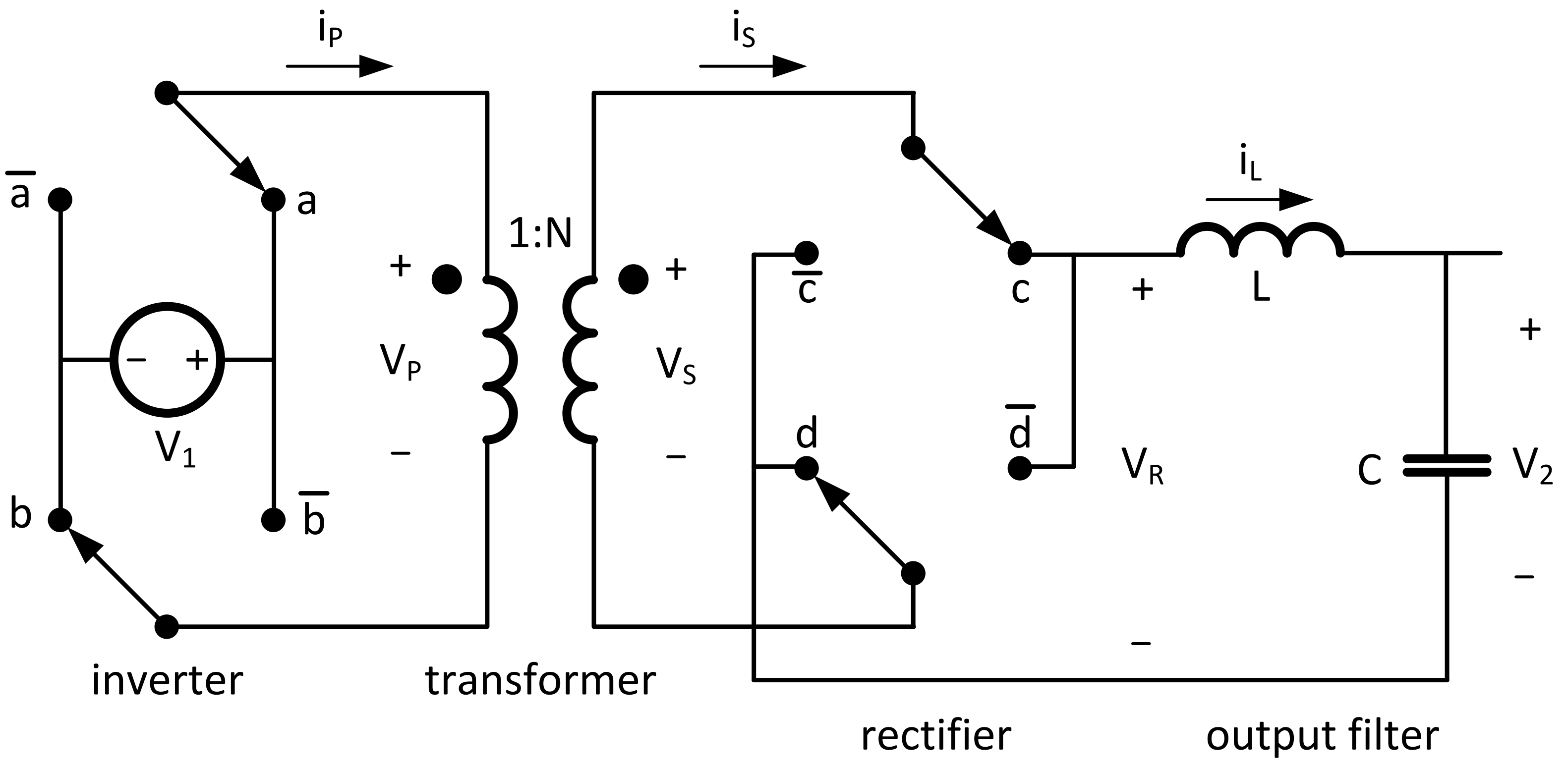
$$V_S = \frac{N_S}{N_P} V_P$$

$$I_S = \frac{N_P}{N_S} V_P$$

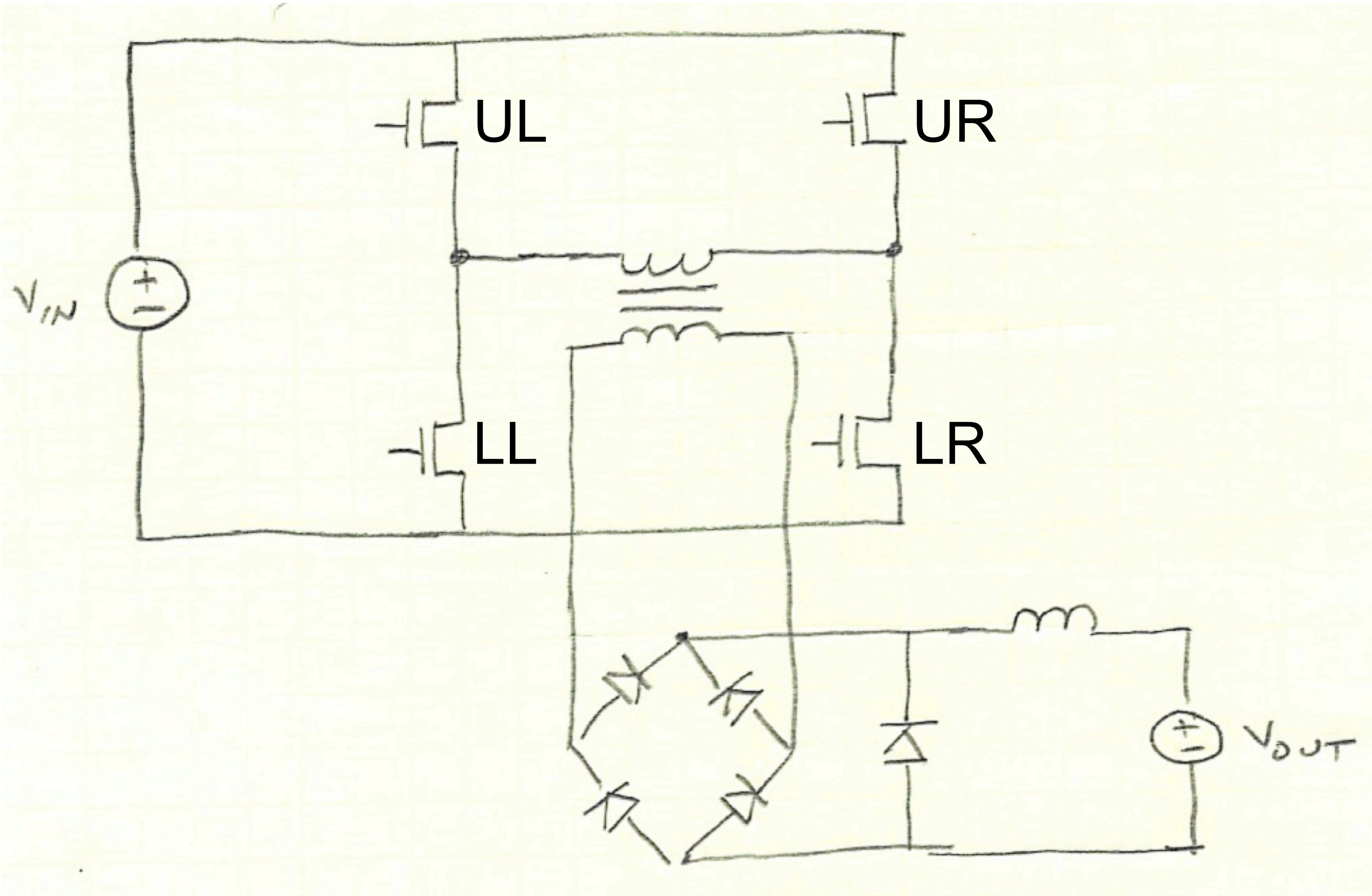
Real Transformer



Full-Bridge Converter



Full-Bridge Converter

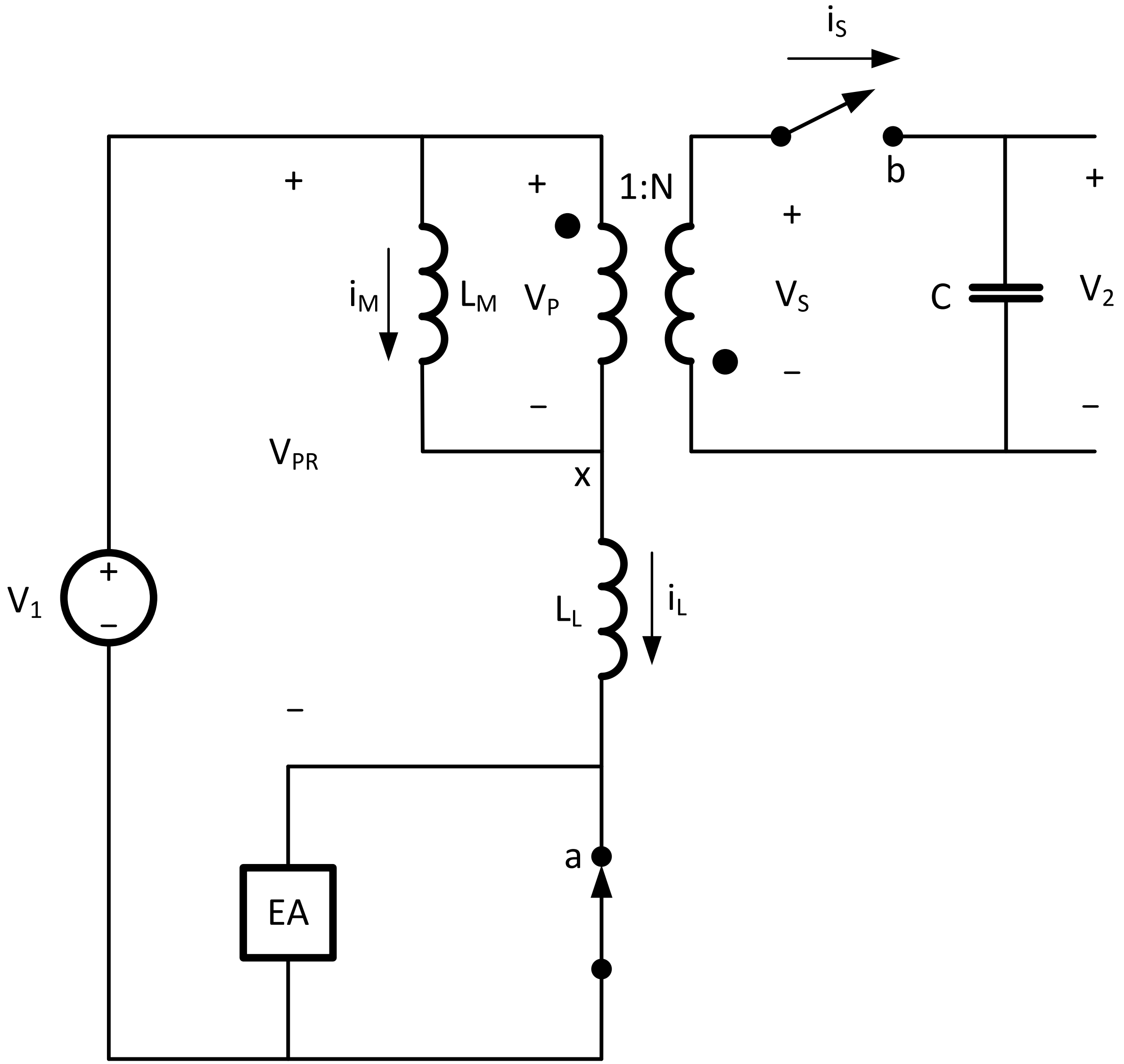


Periodic Steady State Analysis of Full Bridge

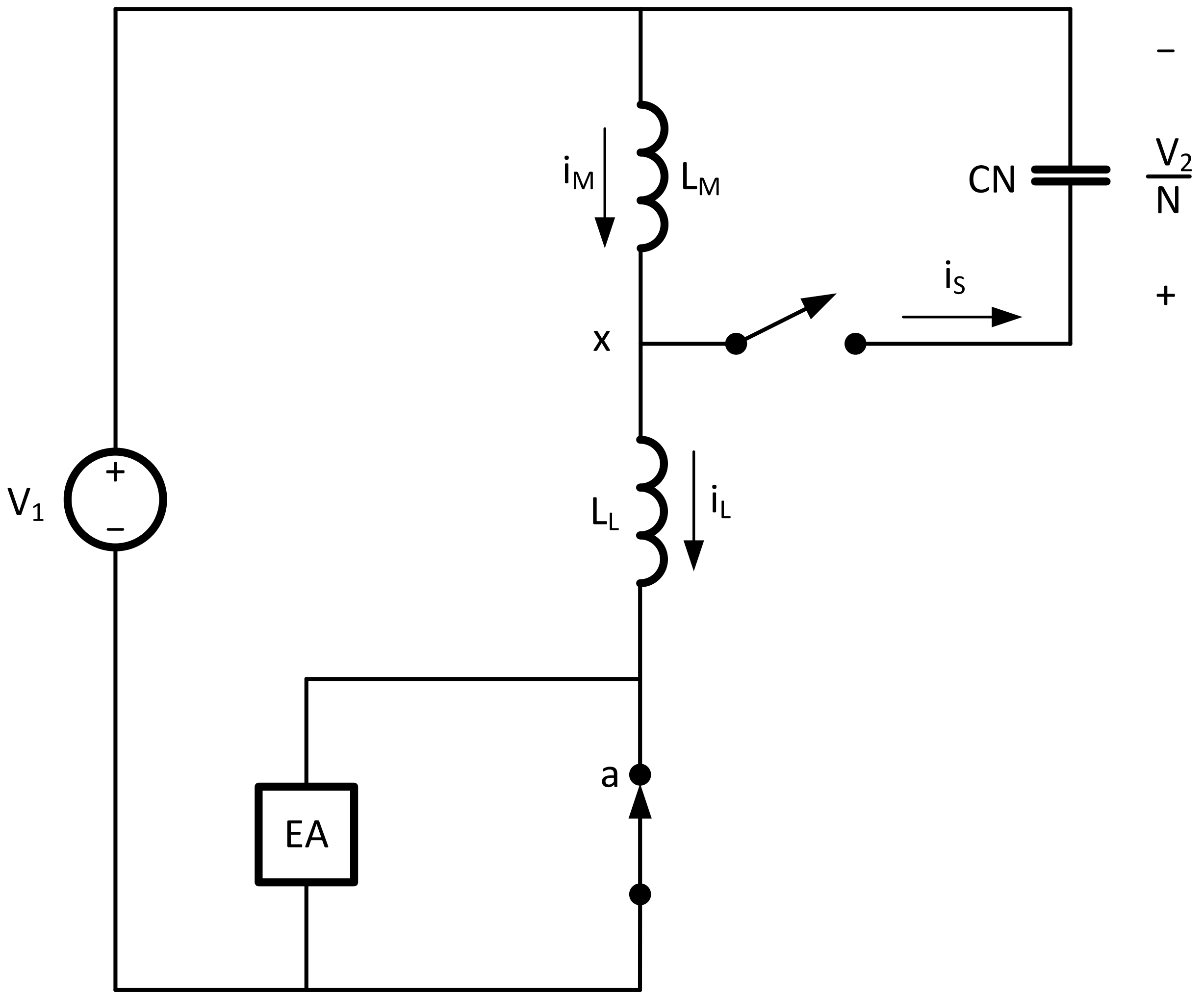
- Suppose V_1 = 10V, transformer is 1:10, what duty factor gives V_2=50V (ignoring leakage inductance)

- Now if primary referenced leakage inductance is 10μH i_L = 10A, t_{cy} = 10μs, what duty factor is needed?

Flyback Converter



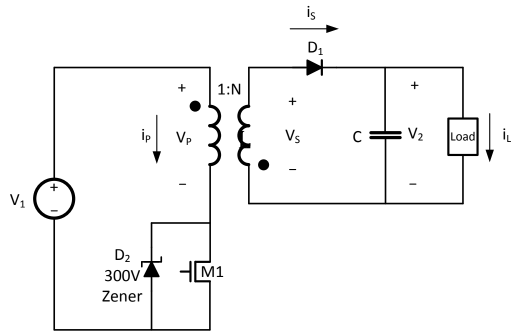
Flyback Converter
With L_M and L_L and Transformer Eliminated



Flyback Converter

- Assume no leakage inductance
- Magnitizing inductance is 50uH
- Input voltage and output voltage both 100V
- If 1A load current, 16us cycle time, and 1:1 transformer
- How long an on period is required?

Problem 6: Flyback Converter [20 Points]



Consider the flyback converter shown in the figure above. The input supply is 50V. The transformer has a 1:2 turns ratio. The magnetizing inductance of the transformer is 20μH, and its primary-referenced leakage inductance is 1μH. The load current is 1A. The converter has a 10μs cycle time and operates in **discontinuous conduction mode** (i.e., the magnetizing current goes to zero before the end of each cycle).

(a) [5 Points] Ignoring the leakage inductance, what duty factor is required to give an output voltage of 100V in the steady state? (Hint: the duty factor depends on the output current.)

(b) [5 Points] What is the peak magnetizing current in this configuration?

(c) [5 Points] Considering the leakage inductance, what duty factor is required to give an output voltage of 100V in the steady state?

(d) [5 Points] How much energy is lost in the Zener diode each cycle?

Motor Control

Motor Equations

$$V = |L|(v \times B)$$

$$V = K_M \omega$$

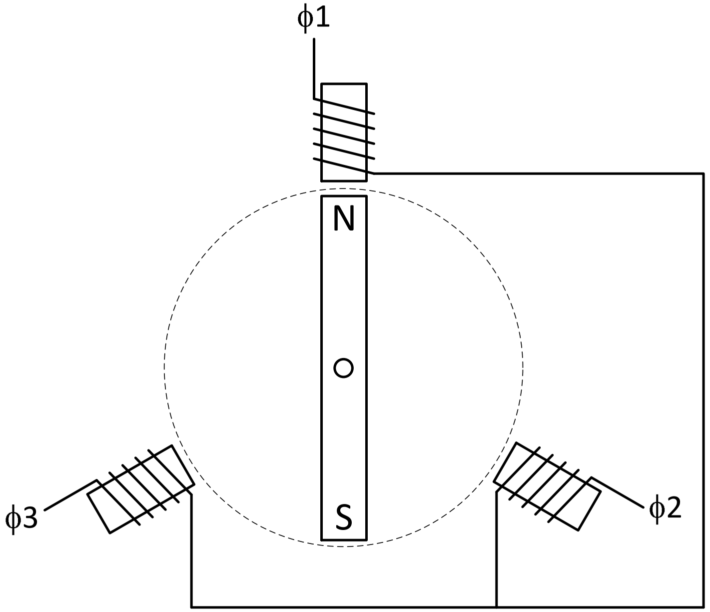
$$F = i(L \times B)$$

$$\tau = K_M i$$

$$\tau = \mathcal{I}_{\mathcal{M}}(d\omega/dt)$$

Simultaneously both a motor and a generator

Back EMF



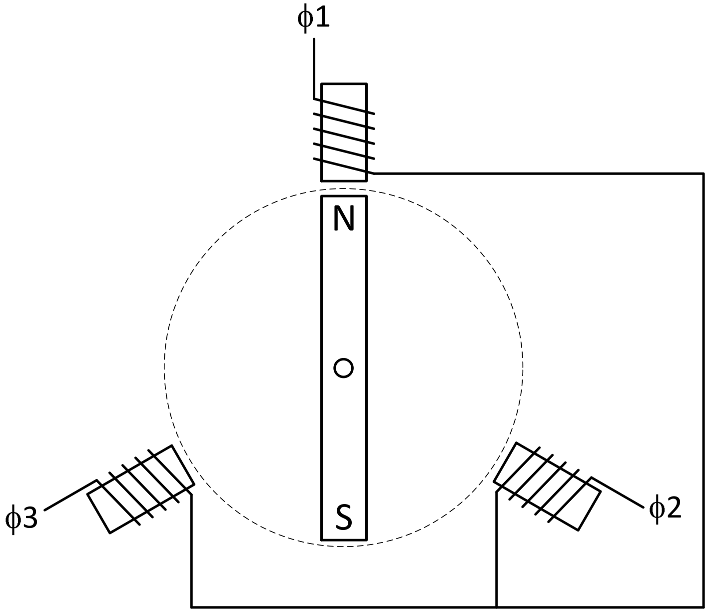
$V(\alpha) = -K\omega\sin(\theta - \alpha)$

Open-circuit voltage (back EMF) of each phase is a sinusoid that

Is proportional to ω

Reaches peak value when rotor is 90 degrees from phase.

Torque



$\tau = -(Ki)\sin(\theta - \alpha_i)$

Torque is proportional to current

Torque is maximum when rotor is 90 degrees behind phase

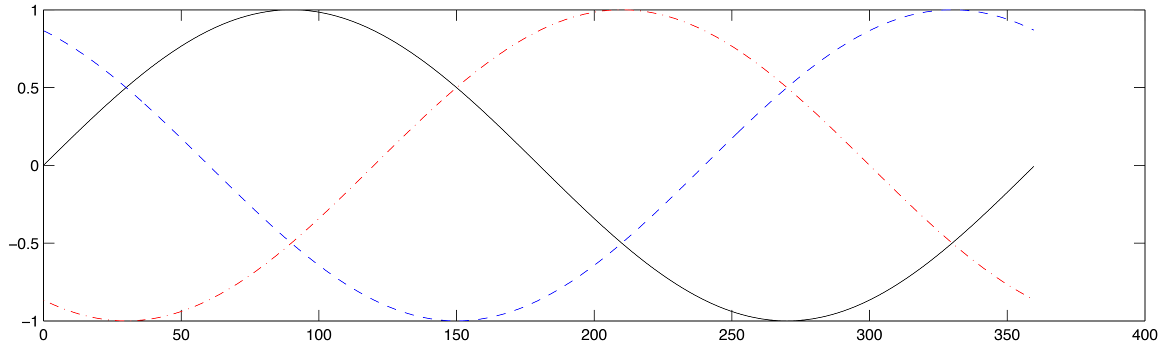
Torque from each phase is sinusoidal

Example

- Suppose K_M=1, R_M=1, θ=30deg, ω=10rad/s, V=100V
- What duty factor should be applied to each phase to give 1N-m torque?

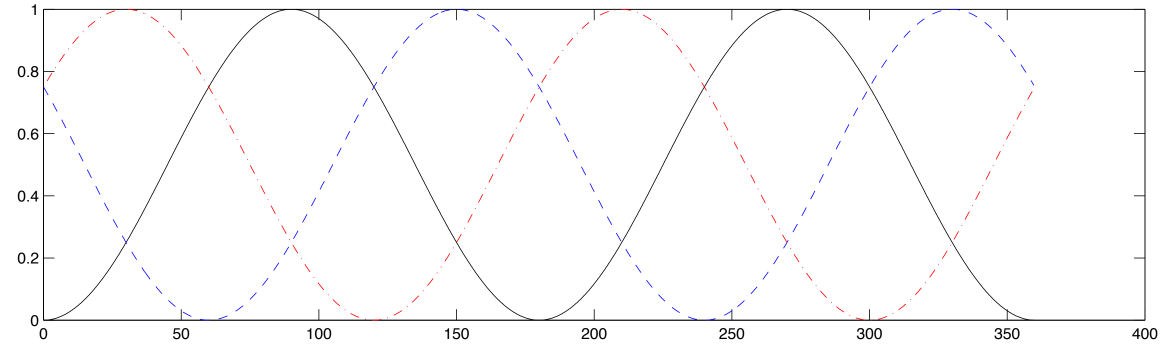
Three-Phase Explained Graphically

$\mathrm{Sin}(\theta - \phi_i)$



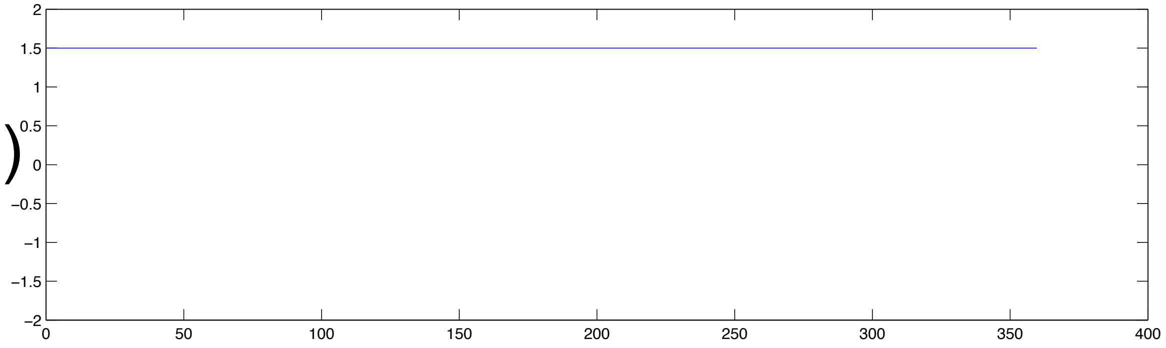
Current

$\mathrm{Sin}^2(\theta - \phi_i)$



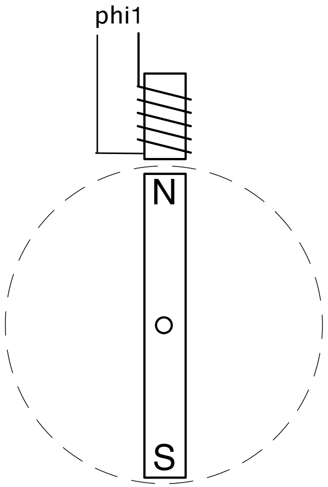
Torque

$\Sigma \mathrm{Sin}^2(\theta - \phi_i)$



Sum of Torque over phases

Problem 2: Motors [20 Points – 5 points each]



Suppose you have a single-phase brushless permanent magnet motor (as shown above). The rotor is shown in the $\theta=0$ position. You may neglect the inductance in the motor windings.

(a) When the motor has an angular velocity of $\omega=2$ rad/s you observe a sine wave with amplitude 1V (RMS) and frequency of 2 rad/s across the single open-circuit winding. If you increase the angular velocity to $\omega = 4$ rad/s, what voltage waveform will you see across the winding? (Express voltage as a function of time, t).

(b) You apply a torque of 2 N-m to the shaft of the motor rotating at 10 rad/s in the direction of rotation. What resistance must be applied across the winding to keep the motor at a steady speed?

(c) Driving the winding with a DC current source with current I_0 and the rotor "locked" in a stationary position, you observe a torque of 1 N-m with the rotor at $\theta=30$ degrees. What torque do you expect with the same current and the rotor at $\theta=90$ degrees?

(d) What torque do you expect at $\theta=90$ degrees and a current of $2I_0$?

Control

Consider the Following Plants

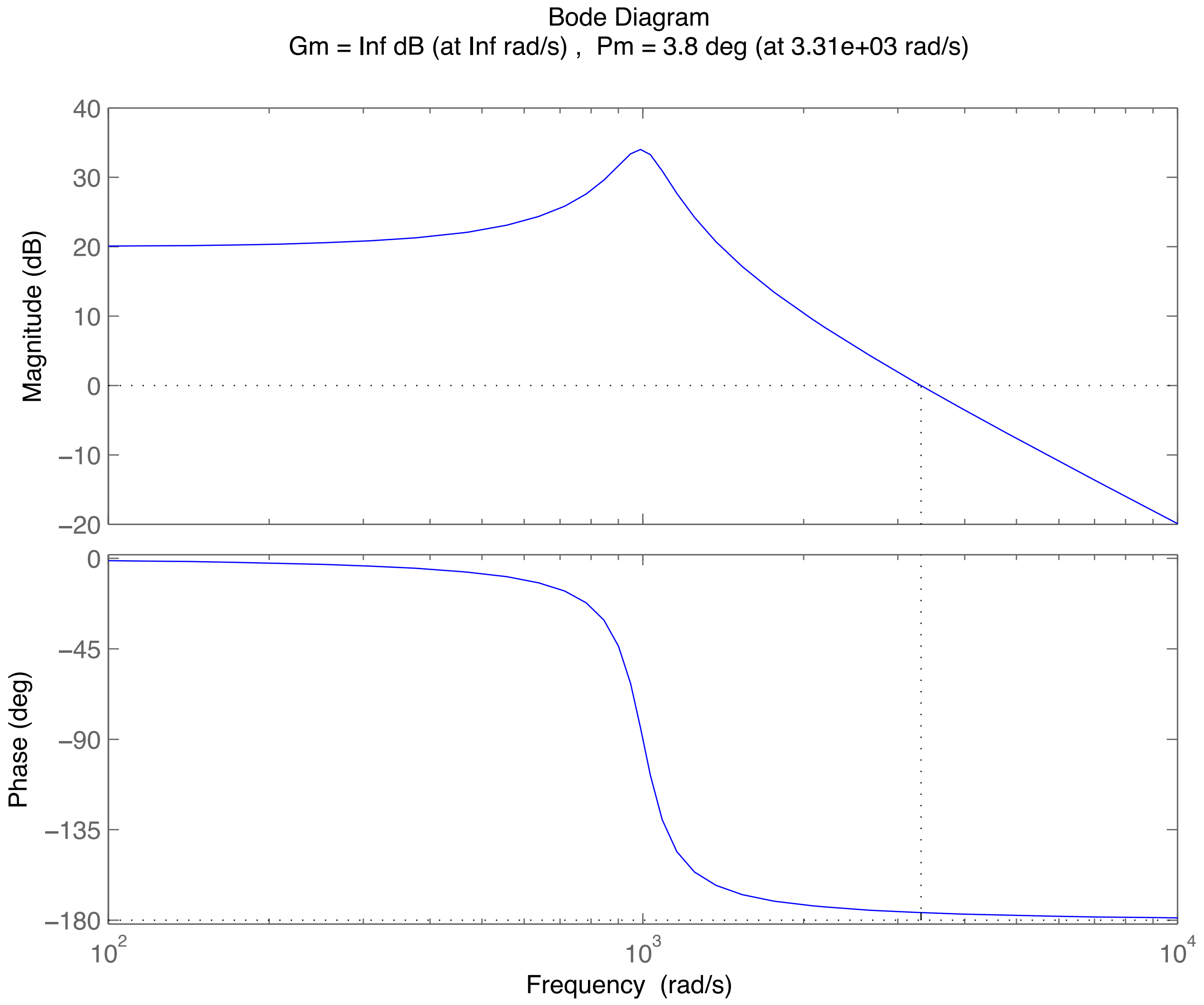
$$\frac{1}{s+a}$$

$$\frac{1}{s^2 + 2\zeta\omega s + \omega^2}$$

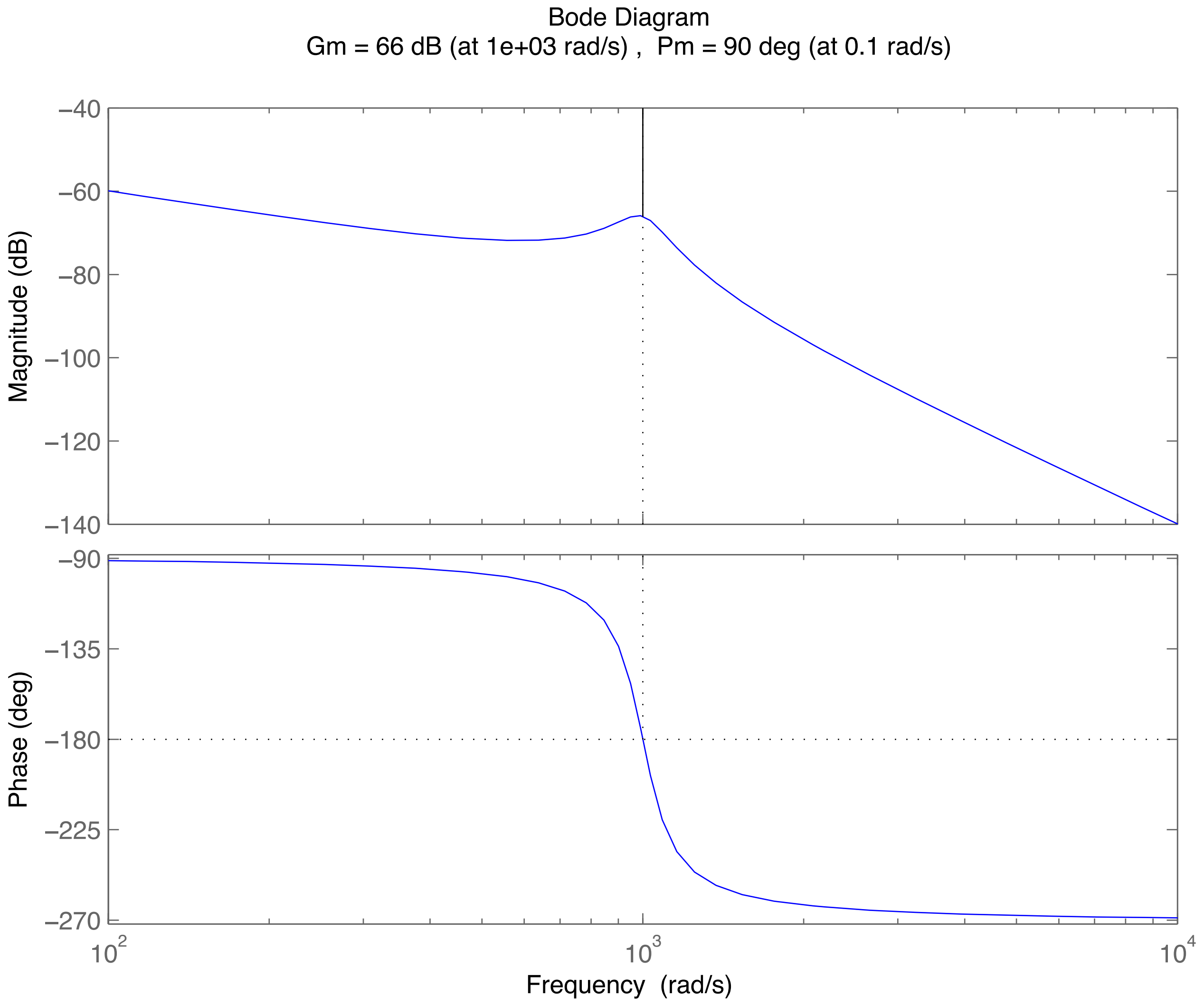
What type of controller do we need for each?

What should the parameters of our controller be?

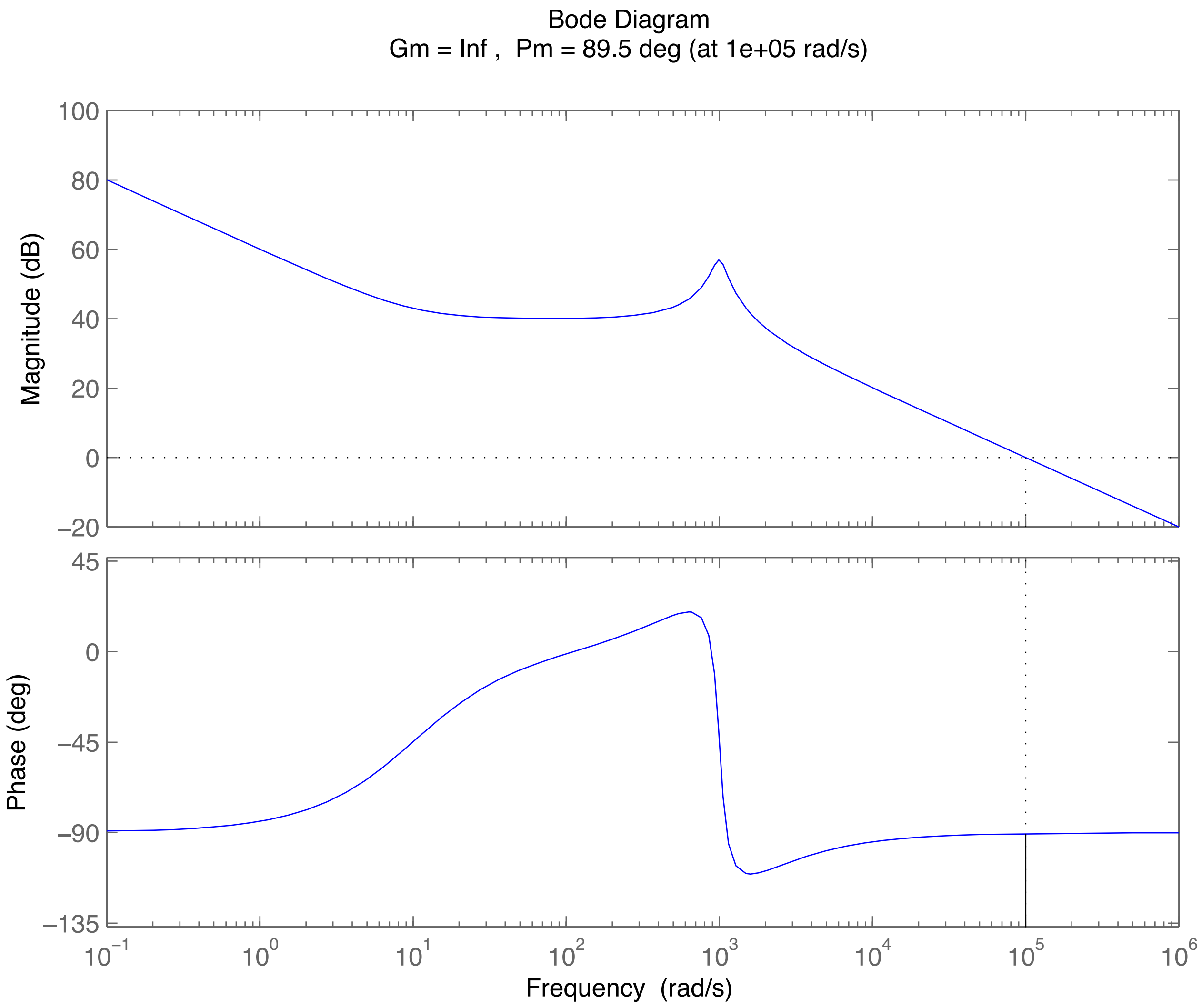
Bode Plot for ζ=0.1 ω=1000



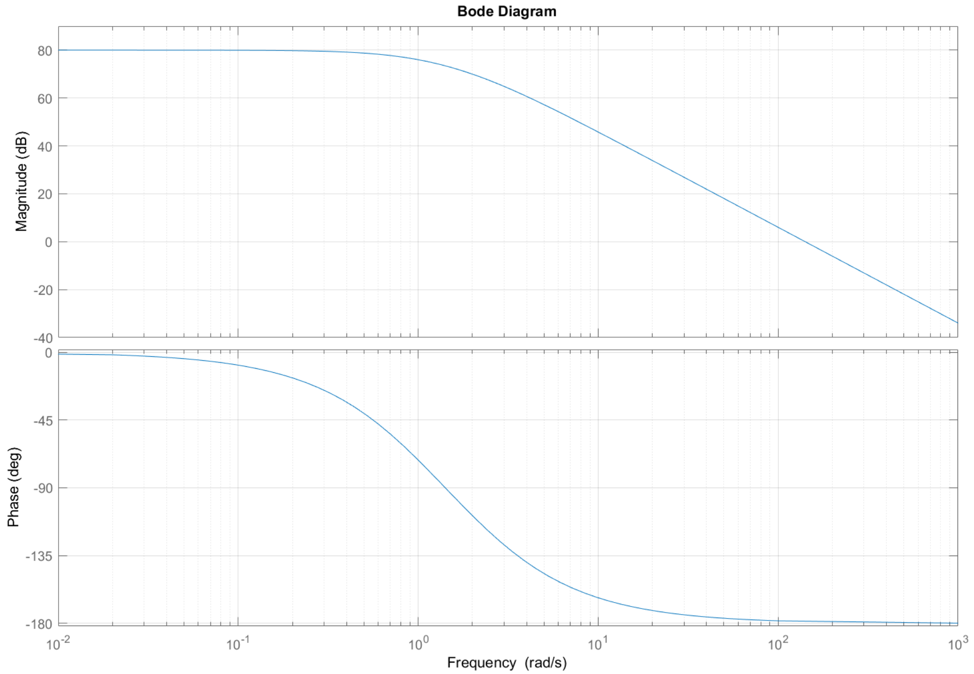
Approach 1 – Integral Only – Low Gain



Approach 2 – PDI – Large Gain Compensating Zero



Problem 4: Feedback Control [20 Points]



You have a plant with the open-loop frequency response as shown in the Bode plot above. The DC gain is 10^4, there is one pole at -1 rad/s, and one pole at -2 rad/s. Suppose you close a feedback loop around this system. Answer the following questions about the resulting system:

(a) [5 Points] Is the system adequately damped, i.e., will any ringing after an abrupt transition die out in at most a cycle or two? (yes/no)

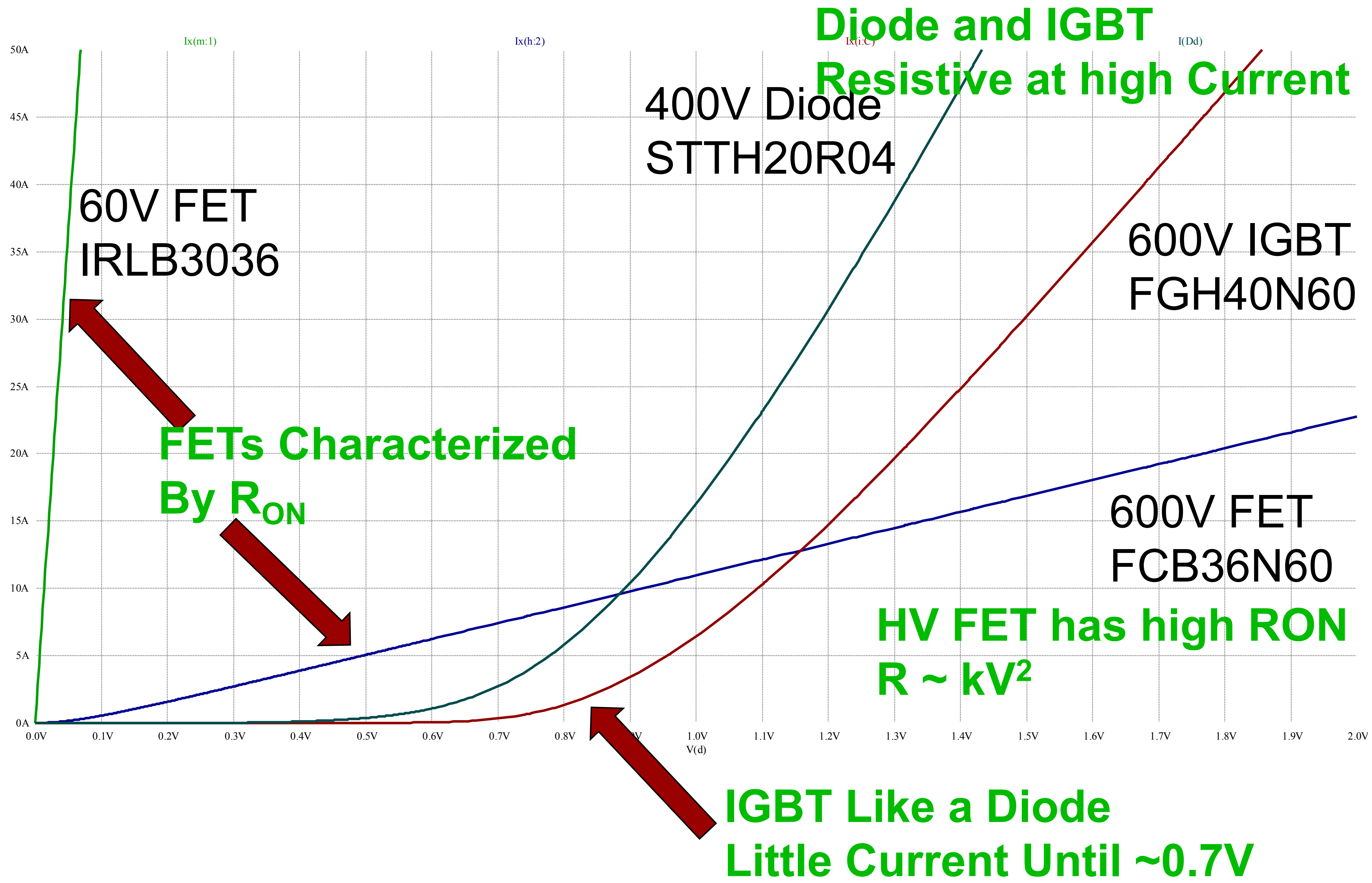
(b) [5 Points] At what frequency in (rad/s) will any ringing occur?

(c) [5 Points] Add a PD controller to the system leaving the DC gain unchanged (i.e., P=1). What is the smallest derivative gain you can add that will give a phase margin of at least 60 degrees? (An approximate answer (within a factor of 2) is OK. You need not be exact.)

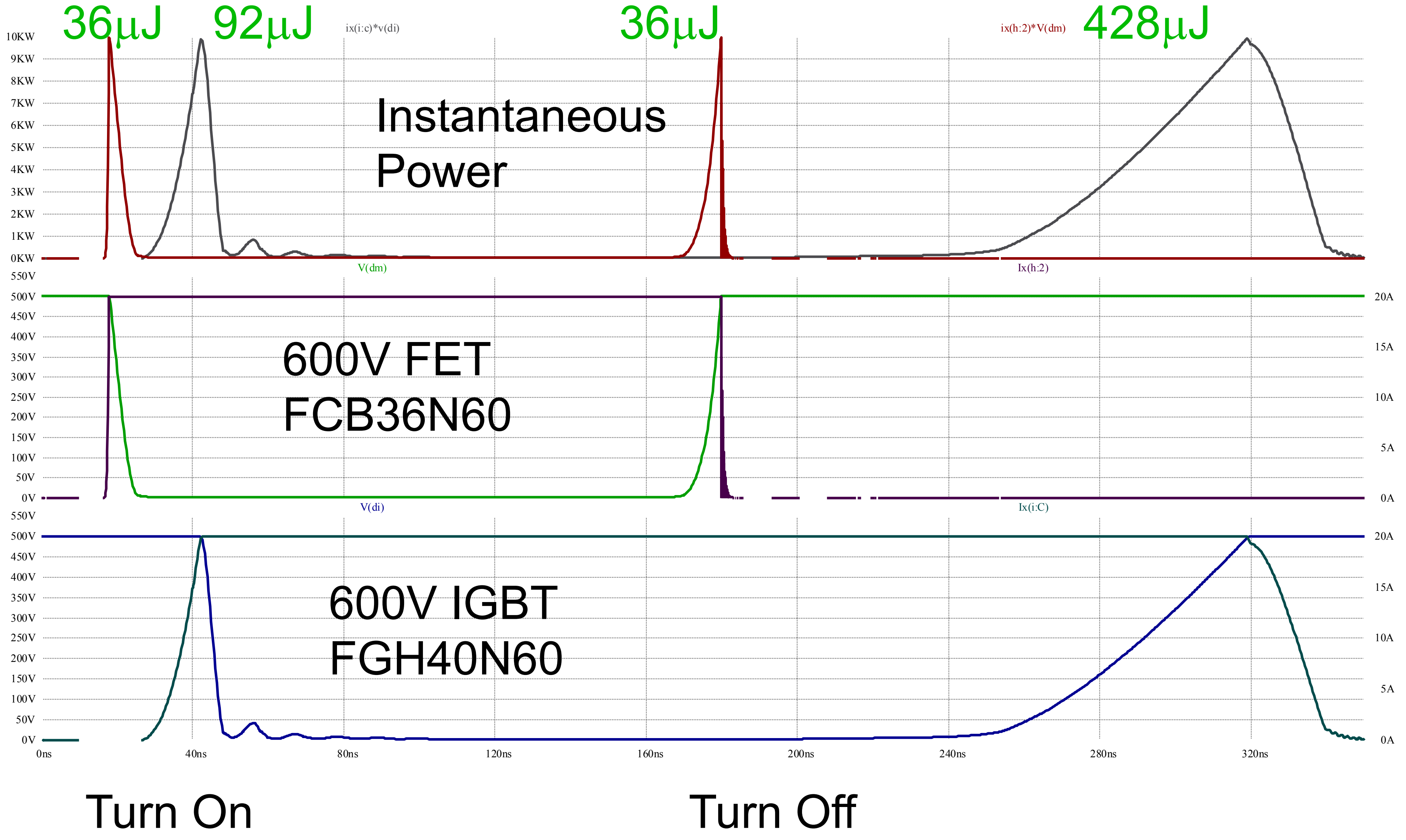
(d) [5 Points] What is the frequency of the zero you added in part (c)?

Switches

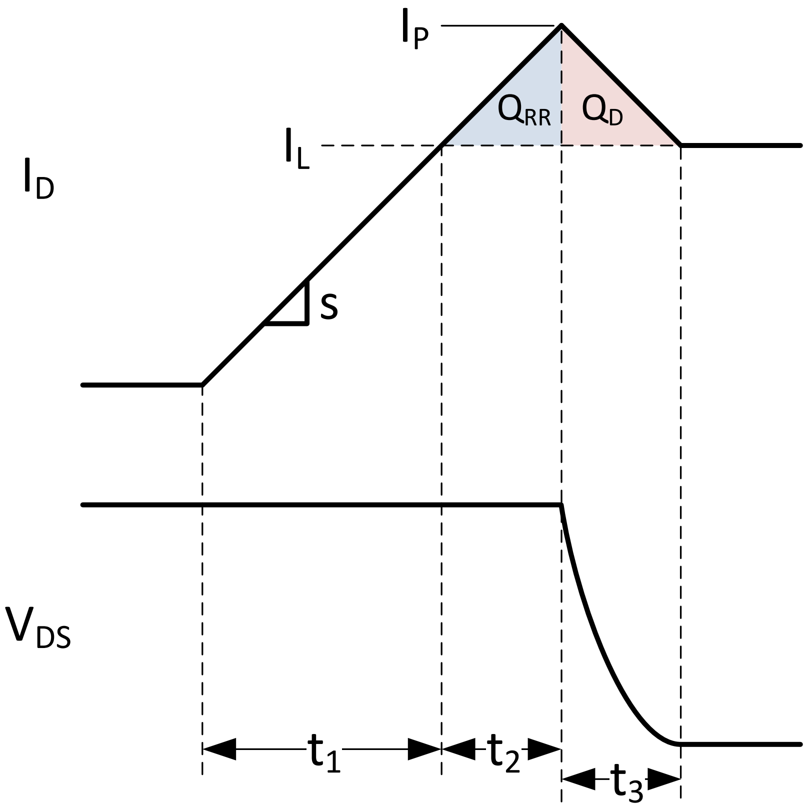
DC I-V Characteristics of On Switches



Transient Response of FET and IGBT



Turn-On
Buck w/ Diode



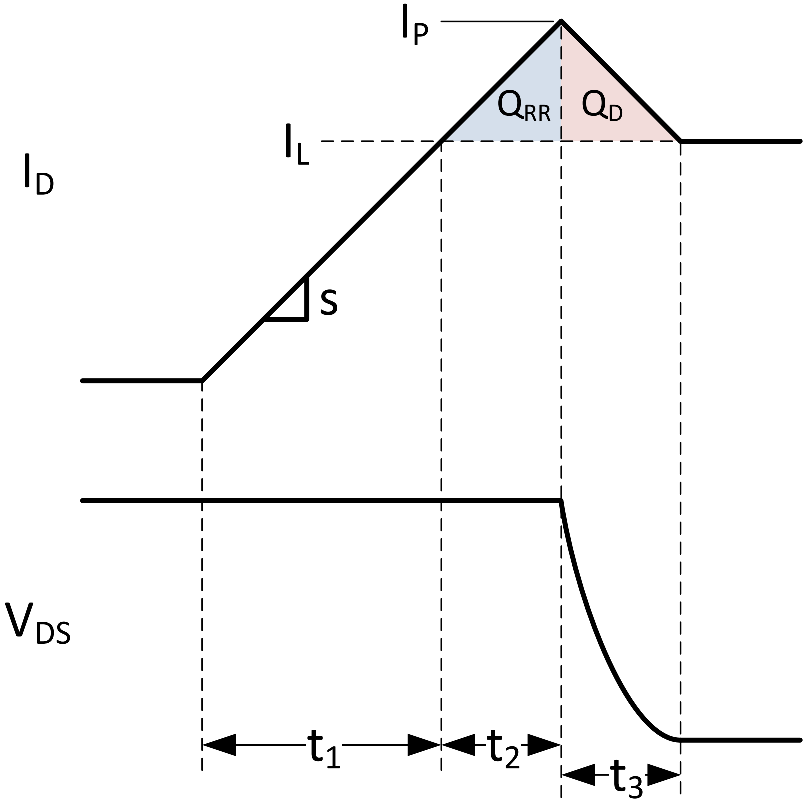
t_1 – ramp current to I_L

t_2 – diode reverse recovery

t_3 – discharge drain capacitance

Current waveform in t_2 and t_3 may vary

Turn-On
Buck w/ Diode



$$t_1 = \frac{I_L}{s}$$

$$E_1 = 0.5 V_{DD} I_L t_1 = \frac{0.5 V_{DD} I_L^2}{s}$$

$$t_2 = \sqrt{\frac{2Q_{RR}}{s}}$$

$$E_2 = V_{DD} t_2 \left(I_L + 0.5 t_2 s \right)$$

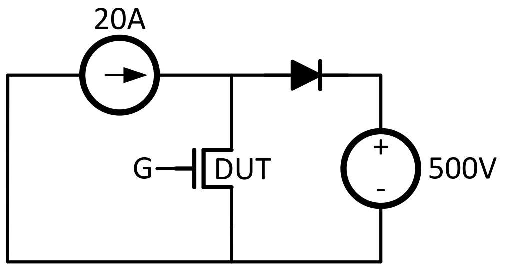
$$t_3 \approx \frac{2Q_D}{I_P}$$

$$E_3 = 0.5 V_{DD} Q_D + 0.33 V_{DD} I_L t_3$$

Switches

- Calculate the switching energy during turn-on for a MOSFET switching 10A through 100V in a buck configuration. Drain capacitance is 1nF, QRR is 25nC. Current ramp is 1A/ns.

Problem 3: FET Losses [10 points, 5 points each]



Consider the boost converter shown above operating in the periodic steady state with a 100kHz switching frequency f_{cy}. Suppose the MOSFET has a Ron of 100mΩ and switches with a linear current ramp of 1A/ns for both turn-on and turn-off. Assume that the capacitance on the drain of the MOSFET is a linear 100pF capacitor and that duty factor D=0.5. Assume the diode has zero forward voltage drop and no reverse recovery charge (i.e., it switches off instantly). Assume that the inductor and capacitor are ideal and that ripple current is negligible. Compute the switching loss and conduction loss of this converter. You may ignore turn-off losses.

PV

- Suppose a single PV panel has
  - V_{OC} = 40V, I_{SC} = 8A, and P_{max} = 250W
- You want to use this panel to provide a 5V supply with the maximum possible current

(a) What converter topology should you use?

(b) What variable should be regulated?

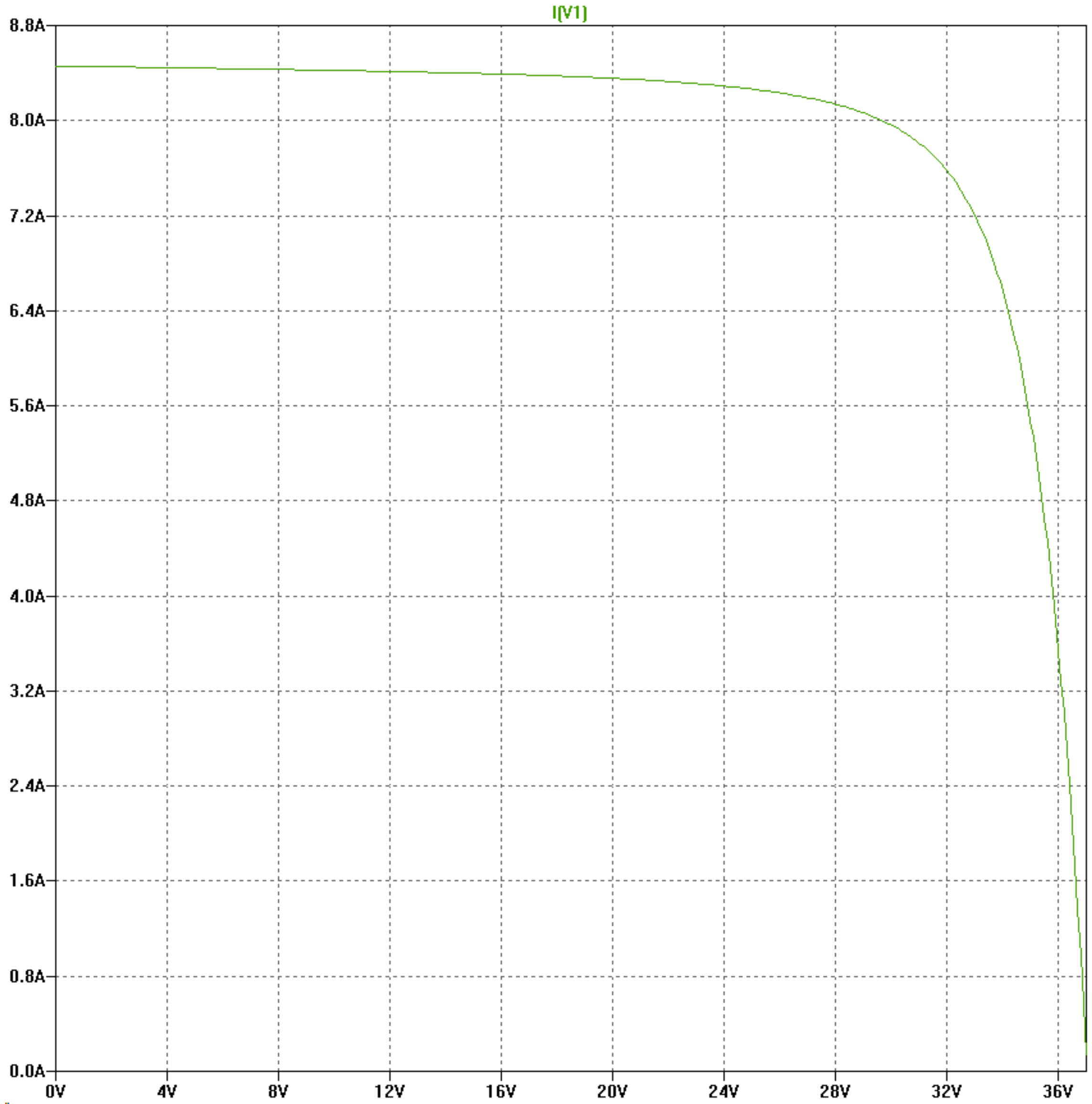
(c) If losses are zero, what will be the maximum current out?

(d) Will the panel be at its MPP when current reaches a maximum?

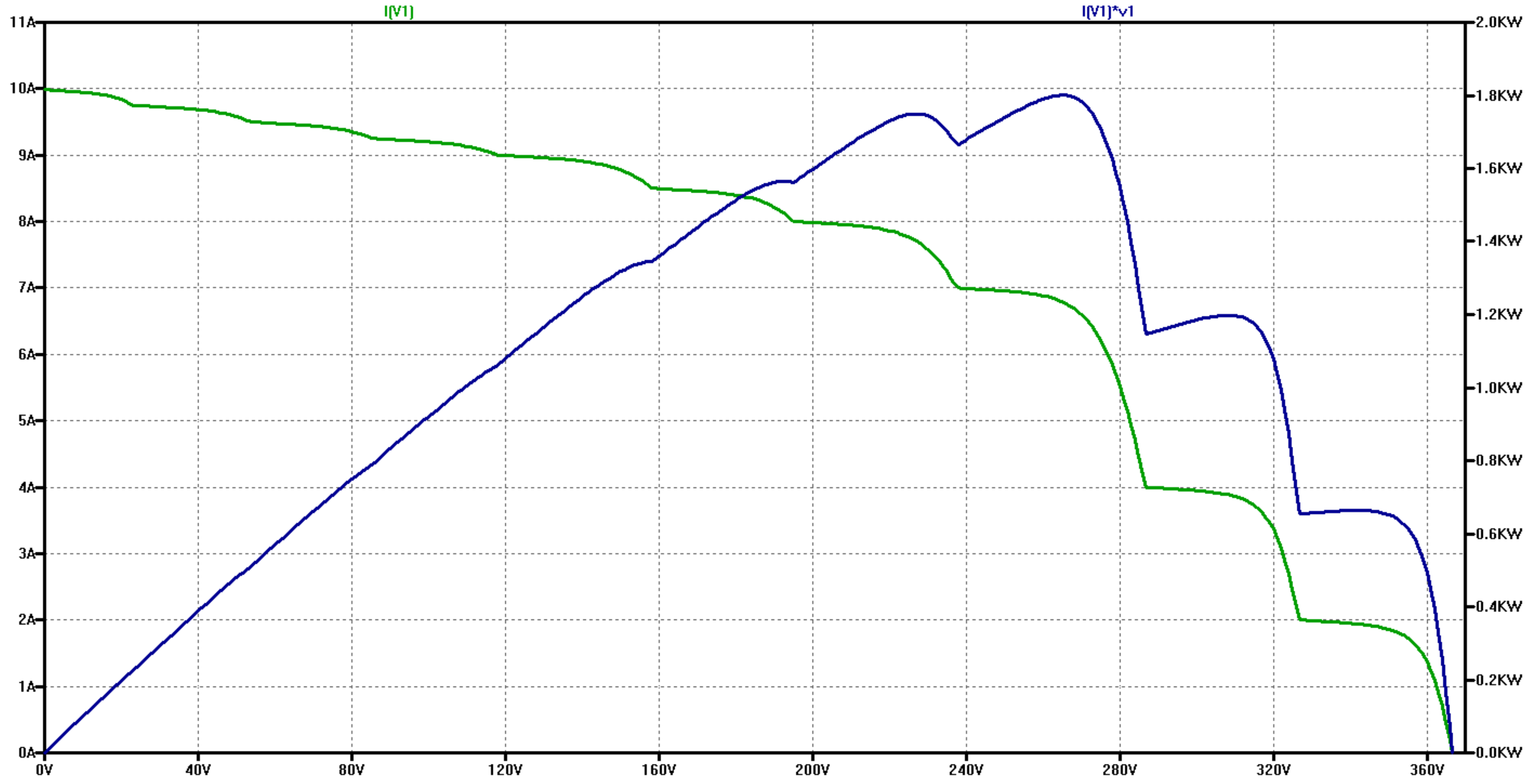
(xc) What control law will provide maximum power beyond the point where 5V can be maintained?

(e) What would your answers be if the output were 100V?

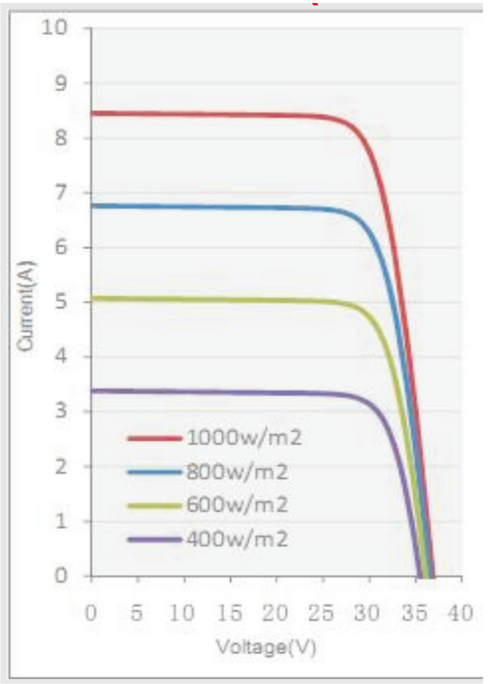
IV Curve from SPICE Model



Typical String of 10 PV Panels



Problem 7: Photovoltaics [15 Points, 3 Points Each]



Suppose I have a string of 3 PV modules. The first two have I-V characteristics given by the 1000W/m² line on the figure above. The third follows the 400W/m² line. The three modules are connected with bypass diodes across each module. Answer each of the following questions about this three module configuration.

(a) What is the approximate open-circuit voltage of the 3-panel configuration?

(b) What is the approximate short-circuit current of the 3-panel configuration?

(c) At the lowest current where the 400W/m² panel bypasses, what are I and V?

(d) What is the approximate maximum power point MPP of the three-panel configuration?

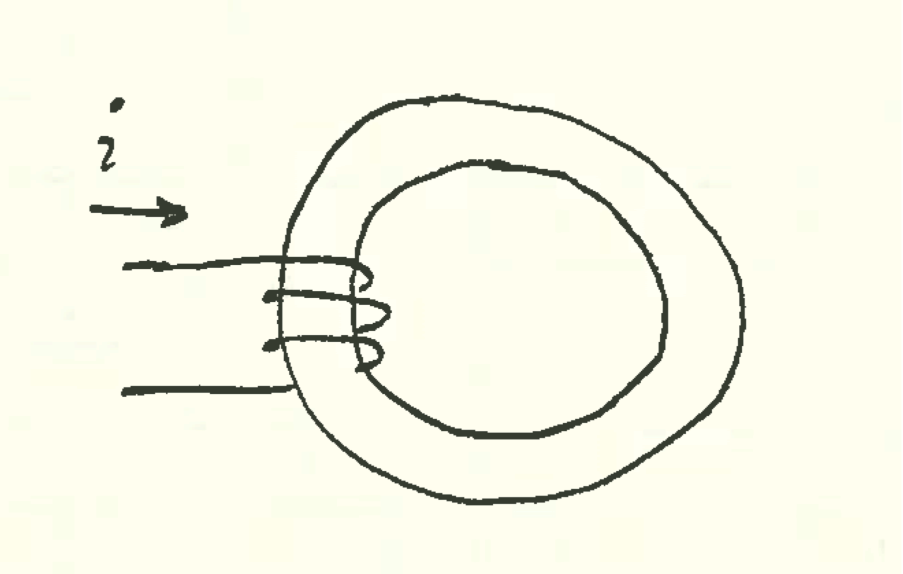
(e) Can the maximum power point be found by gradient search (hill climbing) from both the open-circuit and short-circuit configurations? (yes or no, and explain)

Magnetic Components

A Magnetic Circuit

- Put N turns of wire on a magnetic core
- Pass current i through resulting coil
- Produces *Magnetomotive Force*

$$\mathcal{F} = Ni$$



- $\mathcal{F}$ induces a flux ϕ in the core

$$\phi = \frac{\mathcal{F}}{\mathcal{R}} = \frac{Ni}{\mathcal{R}}$$

- Where $\mathcal{R}$ is the *Reluctance* of the core
- Change in ϕ causes voltage

$$V = N\frac{d\phi}{dt}$$

Two Key Equations

$$N = \frac{LI_{max}}{B_{max}A}$$

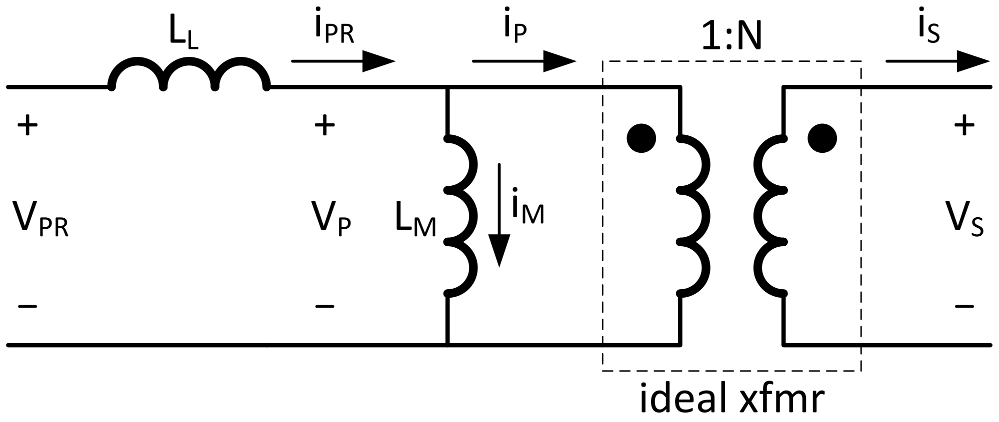
$$l_g = \frac{N^2 \mu_0 A}{L}$$

Inductors

- Suppose inductor for a converter with L=6.25uH and I_{max}=11A has
- A_c = 1E-4m^2
- L_c = 1E-2m
- μ = 1000
- f = 100kHz
- B_{max} = 0.1T

- What gap is needed? How many turns?

Transformers



$$V = N\frac{d\phi}{dt}$$

$$VT = N\phi$$

$$VT = NBA$$

$$N = \frac{VT}{BA}$$

Problem 5: Transformer Design [20 Points, 5Points Each]

The relevant properties for a Ferroxcube E20/10/5 core are shown in the table below. In the 3C96 material this core has a μ_r=1530 and $\mathbf{A_L}$**=1.4μH/turns²**. The window area is A_W=100mm², and the length of the average turn is L_{turn} = 38mm. Recall the permeability of free space $\mu_0 = 4\pi \times 10^{-7}$.

SYMBOL	PARAMETER	VALUE	UNIT
Σ(I/A)	core factor (C1)	1.37	mm^{-1}
V_e	effective volume	1340	mm^3
l_e	effective length	42.8	mm
A_e	effective area	31.2	mm^2
A_{min}	minimum area	25.2	mm^2
m	mass of core half	≈ 4.0	g

(a) Suppose you build a transformer by winding a 5-turn primary and a 40-turn secondary on this core. What is the primary-referenced magnetizing inductance of this transformer? (Hint: use A_L).

(b) Starting from zero magnetizing current, how many Volt-Seconds can the primary of the transformer of part (a) tolerate before the B-field in its core reaches 0.5T?

(c) For the core to handle 10^{-4} Volt-Seconds, how many turns would the primary need to have?

(d) For the configuration of part (a), what is the secondary-referenced magnetizing inductance of the transformer?

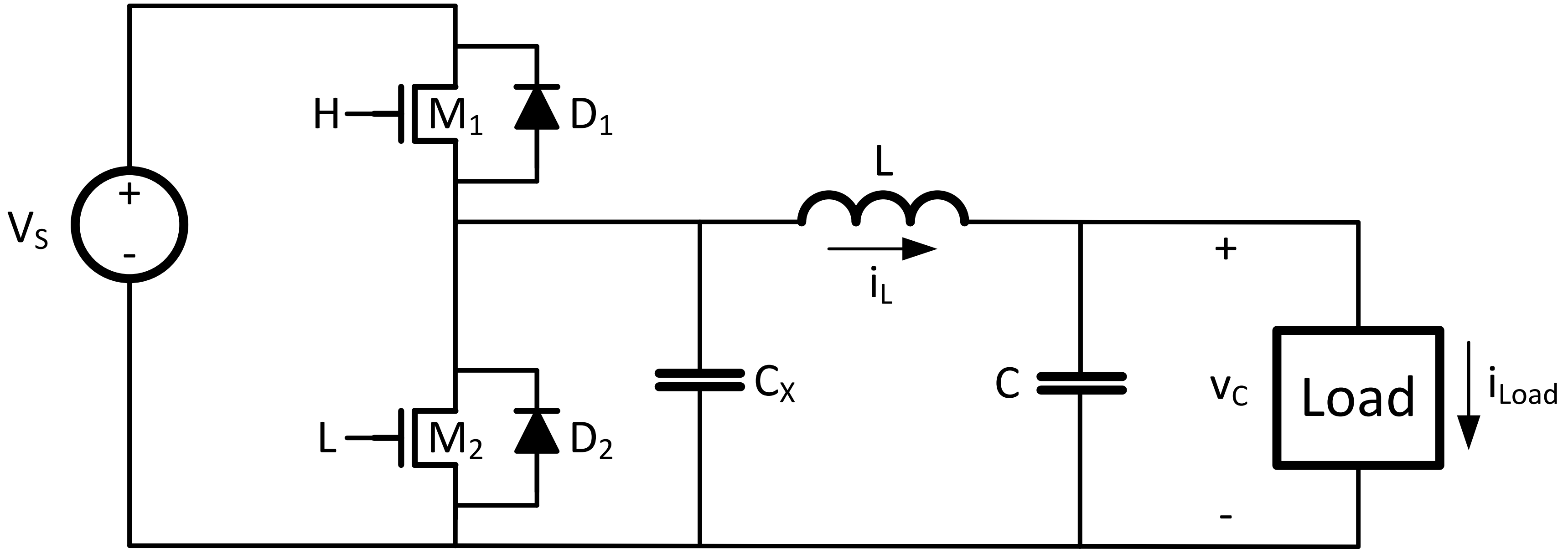
Soft Switching

Soft Switching

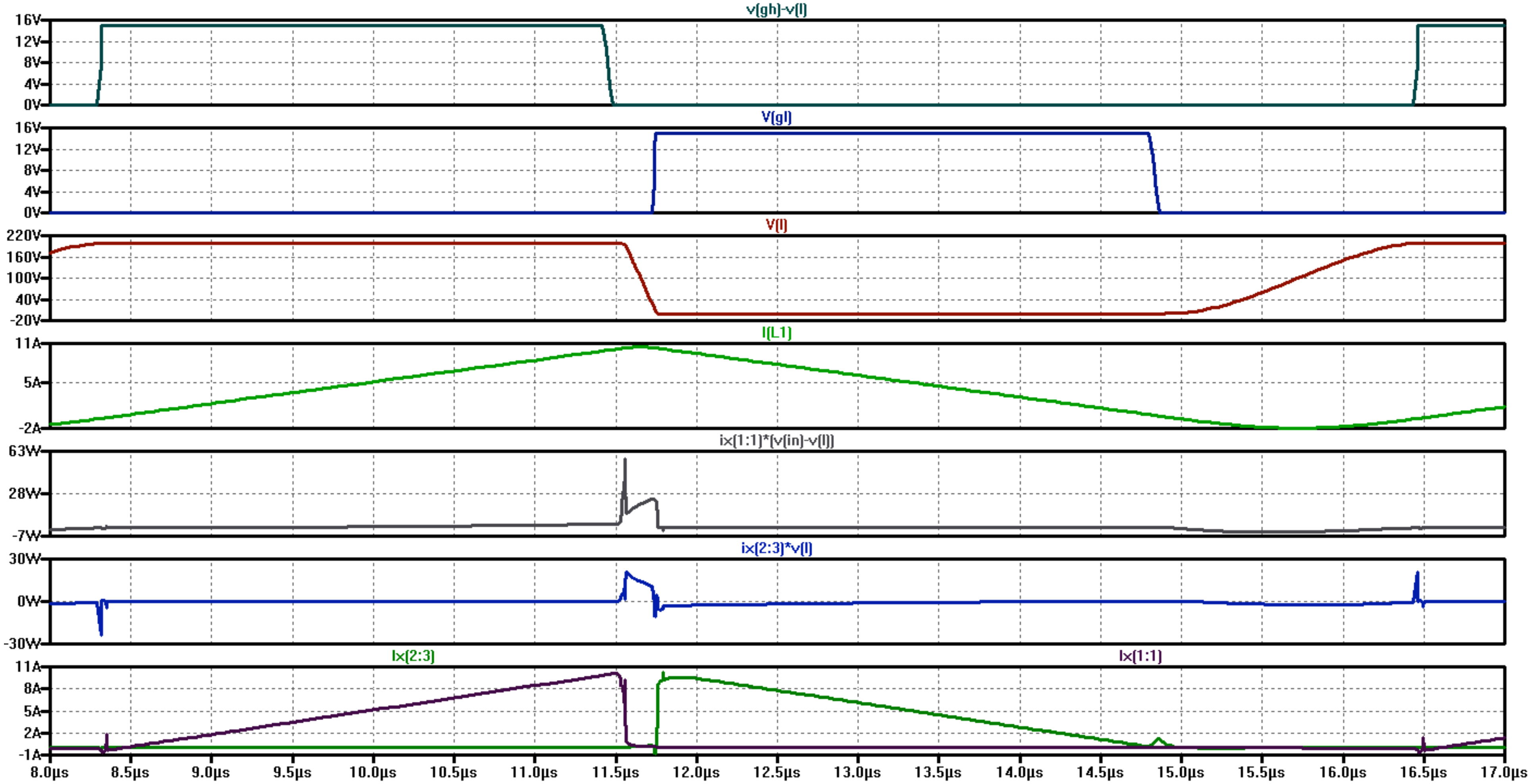
- Only switch a FET when:
  - Zero voltage across it (ZVS)
  - Zero current through it (ZCS)
  - Both

- 4 Approaches
  - Phase-shifted full-bridge
  - Quasi-square wave
  - Quasi resonant
  - Active clamp

QSW Buck Converter



Soft Switched Waveforms



Inverters and Power Factor

Definition

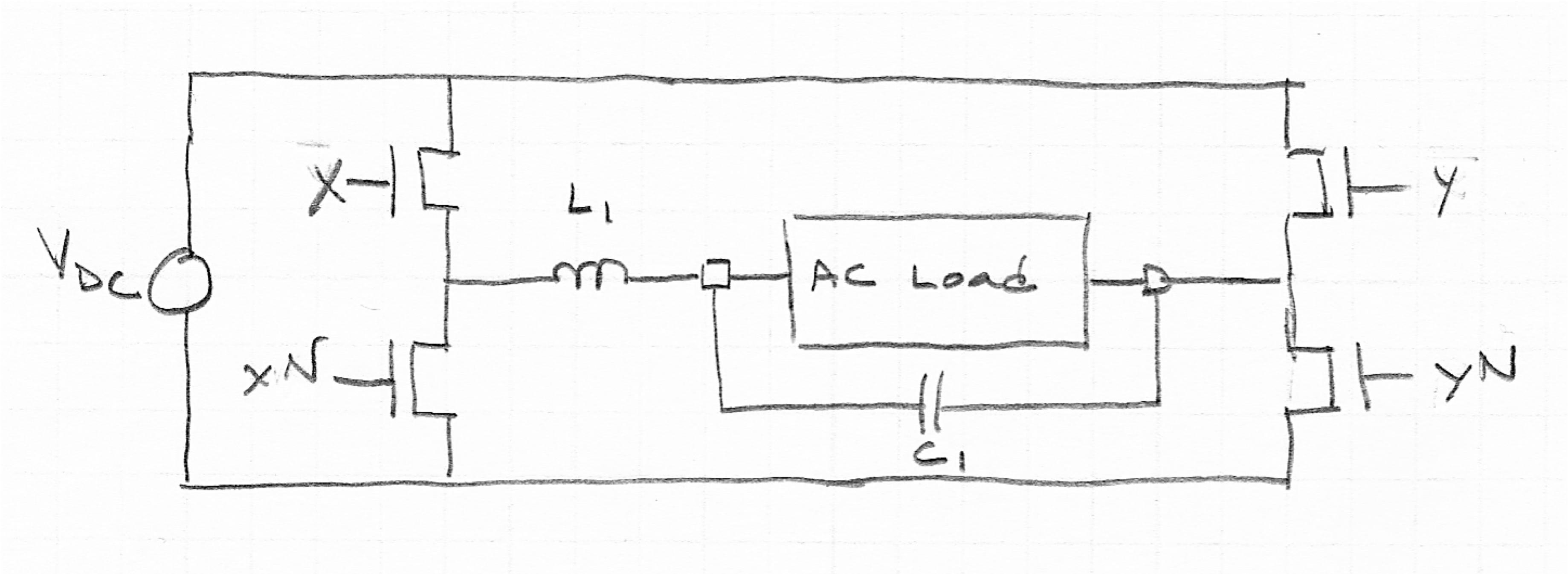
$$PF = \frac{Real\ Power}{Apparent\ Power}$$

Apparent Power = V_{rms} x I_{rms}

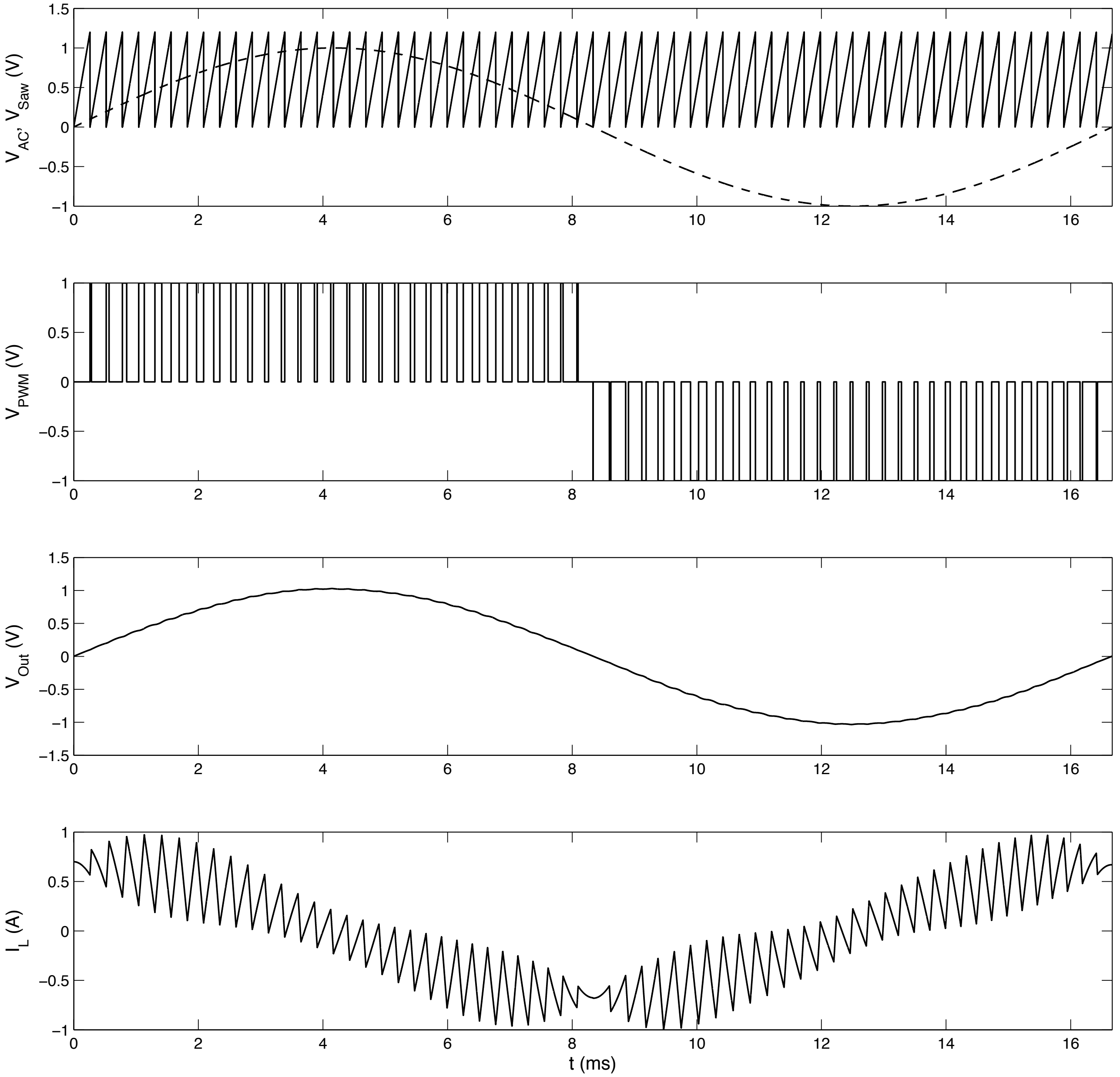
$$PF = \frac{P}{\sqrt{P^2 + Q^2}}$$

$$PF = \frac{1}{\sqrt{1 + THD^2}} = \frac{I_{1,rms}}{I_{rms}}$$

Make a PWM Sine Wave and Filter



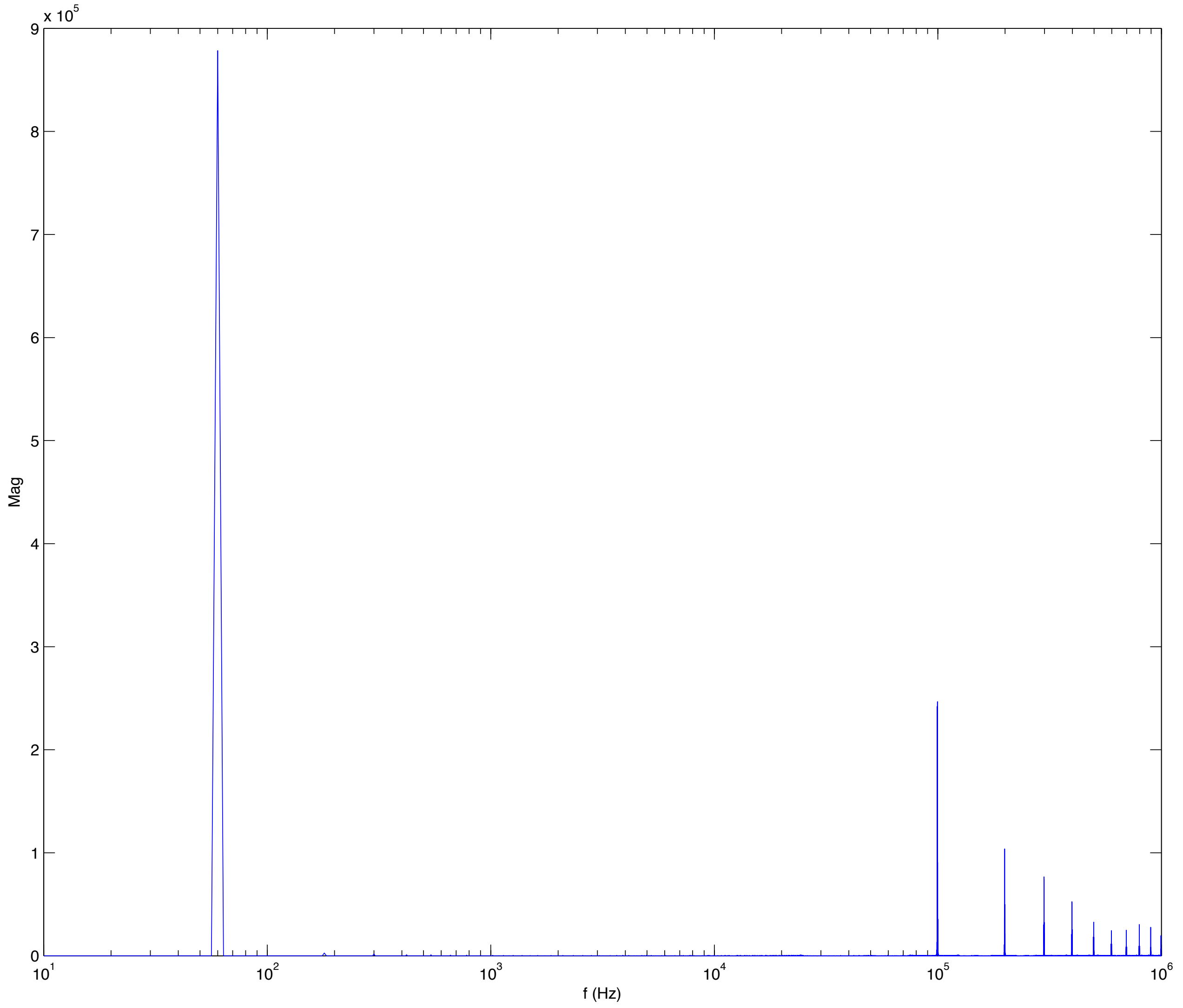
PWM Synthesis



x = sine > saw
y = -sine > saw

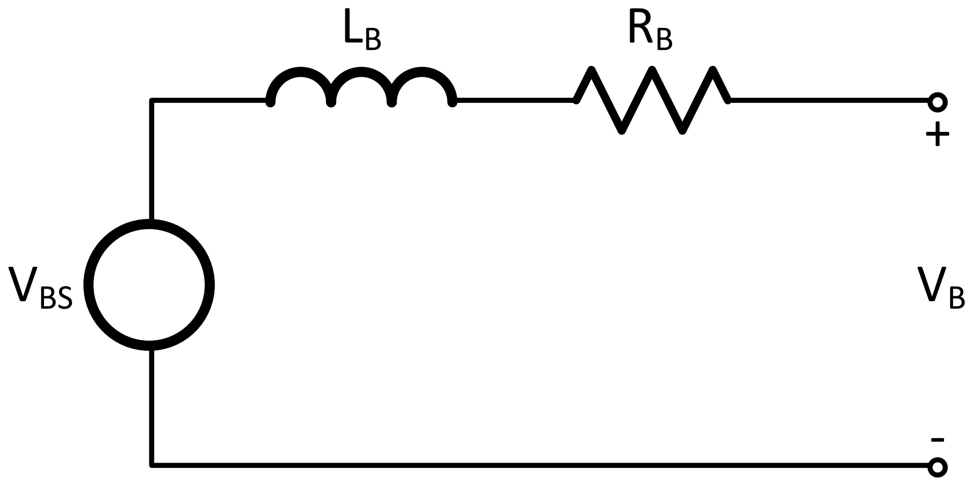
Digitally generate sine with quarter-wave table

Spectrum of 100kHz PWM Signal



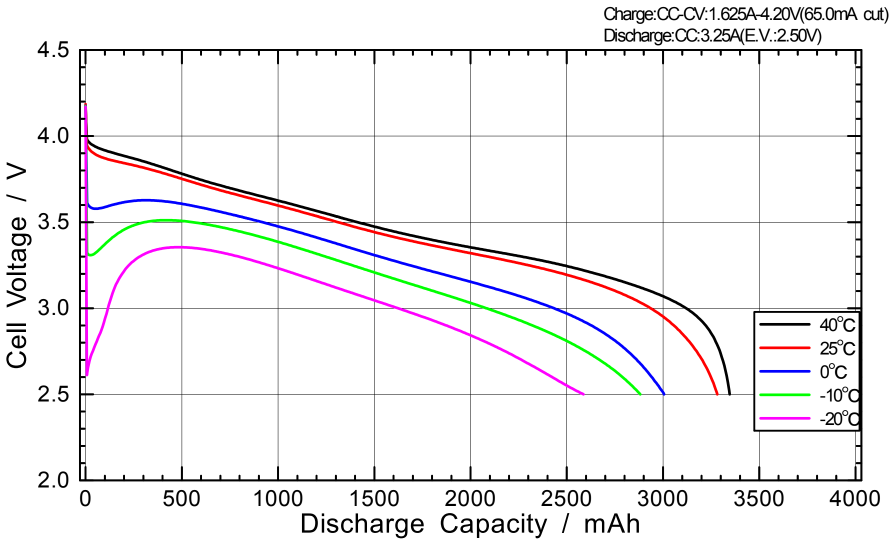
Batteries

Batteries

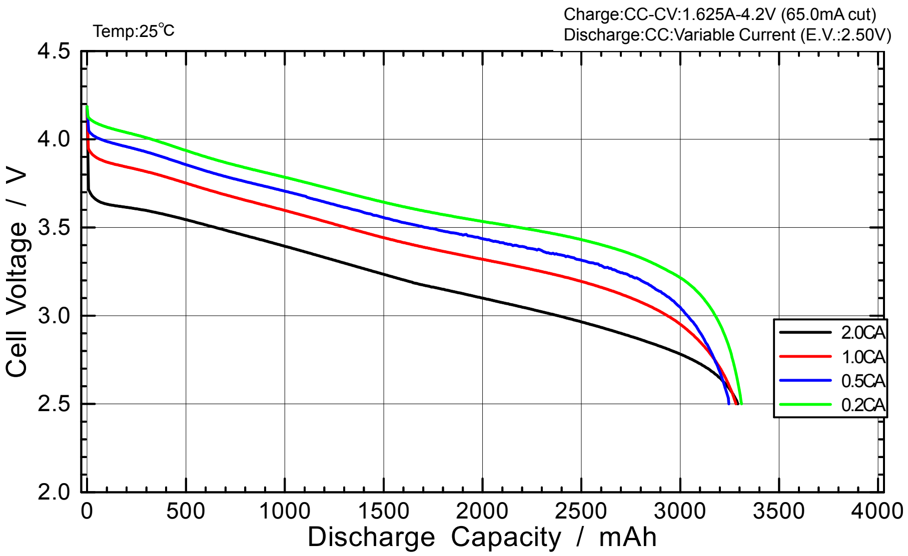


Voltage Surface V(x,T,I)

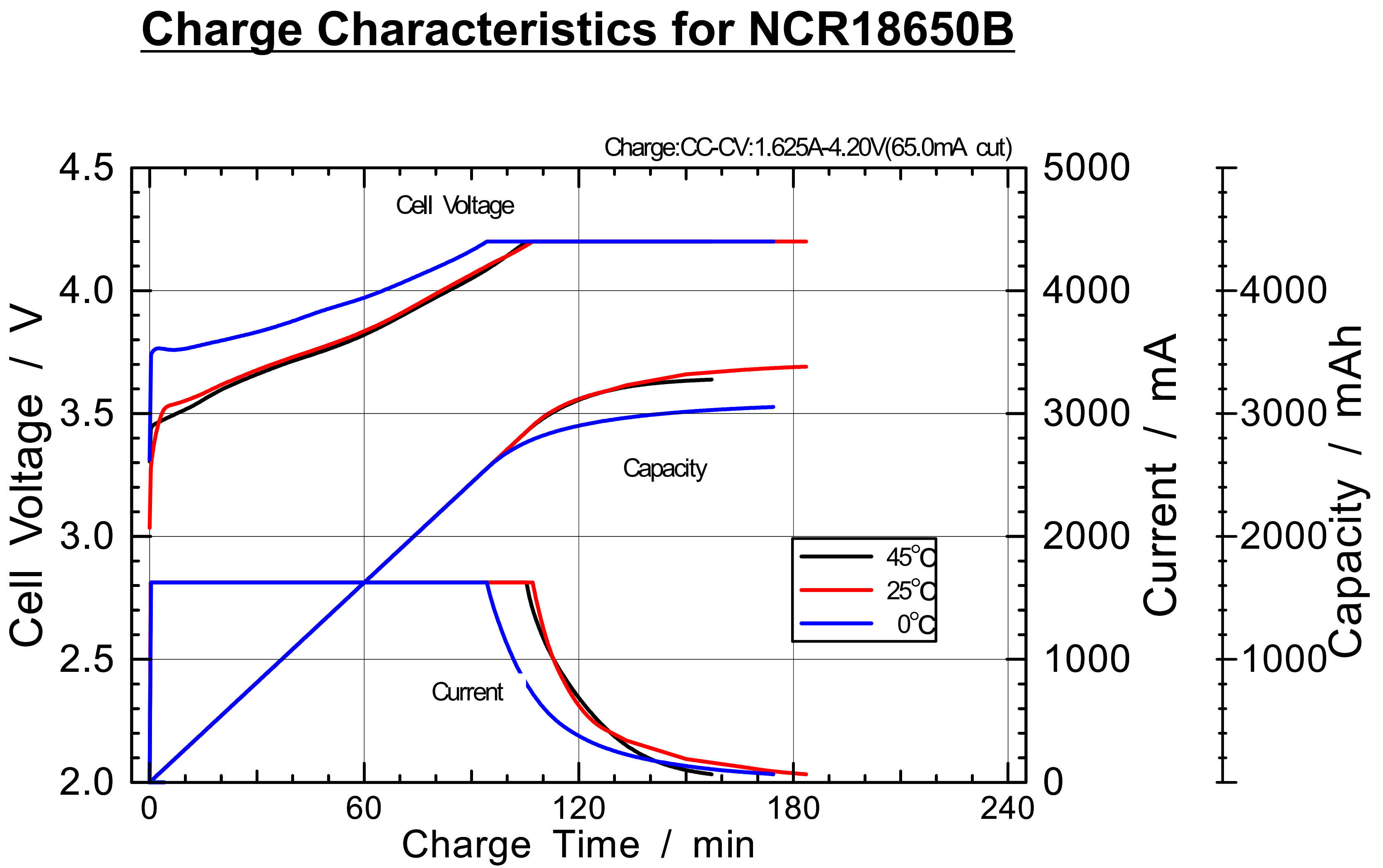
Discharge Temperature Characteristics for NCR18650B



Discharge Rate Characteristics for NCR18650B



Charge Cycle



YAH

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Inverters, Grid, PF, and Batteries	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Thermal & EMI		6	P	6	Project	
14	11/8/17	Grounding, and Debugging						
15	11/13/17	Quiz Review				C1		
16	11/15/17	No Class						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Jon Wagner - Joby						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class				C4		
	TBD	Project presentations			P			
	12/15/17	Project webpage due						