

EE 456

Buck Regulator Design - Continuous Mode Operation

Problem 1 of HW # 2 - Compare calculations of RMS current of the capacitor.

Define useful units for Electrical Engineering

$$\mu\text{s} \equiv 10^{-6} \cdot \text{sec}$$

Specify Input Voltage $V_D := 24 \cdot \text{volt}$

Specify Output Voltage $V_o := 7 \cdot \text{volt}$

Specify Switching Frequency $F_S := 20 \cdot \text{kHz}$

$$T_S := \frac{1}{F_S} \quad T_S = 50 \cdot \mu\text{s}$$

Find on time assuming continuous mode operation. $t_{\text{on}} := \frac{V_o}{V_D} \cdot T_S$ $t_{\text{on}} = 14.583 \cdot \mu\text{s}$

Specify the Max output Current $I_o := 3 \cdot \text{amp}$

Design the buck regulator so that it operates in the continuous mode for currents down to 10% of the max current.

$$I_{o_min} := 0.1 \cdot I_o \quad I_{o_min} = 0.3 \cdot \text{amp}$$

Find L so that the buck regulator operates in continuous mode for the min output current

$$L := \frac{V_D - V_o}{2 \cdot I_{o_min}} \cdot t_{\text{on}} \quad L = 413.194 \cdot \mu\text{H}$$

Choose the next size std. inductor $L := 390 \cdot \mu\text{H}$

With chosen inductor, find min current for continuous operation

$$I_{o_min} := \frac{V_D - V_o}{2 \cdot L} \cdot t_{\text{on}} \quad I_{o_min} = 317.842 \cdot \text{mA}$$

For the Max output current, find I1 and I2

$$I_1 := I_o \quad I_2 := I_o$$

Given

$$\frac{I_2 + I_1}{2} = I_o$$

$$I_2 - I_1 = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} := \text{Find}(I_1, I_2) \quad I_2 = 3.318 \cdot \text{amp} \quad I_1 = 2.682 \cdot \text{amp}$$

$$I_2 - I_1 = 635.684 \cdot \text{mA}$$

For the Min output current, find I1 and I2

$$I_{1_} := I_{o_min} \quad I_{2_} := I_{o_min}$$

Given

$$\frac{I_{2_} + I_{1_}}{2} = I_{o_min}$$

$$I_{2_} - I_{1_} = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_{1_} \\ I_{2_} \end{bmatrix} := \text{Find}(I_{1_}, I_{2_}) \quad I_{2_} = 0.636 \cdot \text{amp} \quad I_{1_} = 0 \cdot \text{amp}$$

$$I_{2_} - I_{1_} = 635.684 \cdot \text{mA}$$

Choose the filter capacitor.

Assume that the major component of the ripple comes from the capacitor ESR

Specify the ripple due to the ESR $V_{RR} := 20 \cdot \text{mV}$

$$\text{ESR} := \frac{V_{RR}}{(I_2 - I_1)} \quad \text{ESR} = 0.031 \cdot \Omega$$

For all electrolytic caps, assume that $\text{ESR} \cdot C = 80 \mu\text{s}$

$$C := \frac{80 \cdot \mu\text{s}}{\text{ESR}} \quad C = 2542.735 \cdot \mu\text{F}$$

Choose the next size std capacitor $C := 3300 \cdot \mu\text{F}$

Calculate the new ESR with the chosen capacitor

$$\text{ESR} := \frac{80 \cdot \mu\text{s}}{C} \quad \text{ESR} = 0.024 \cdot \Omega$$

Find the ripple due to the capacitor:

$$V_{\text{RC}} := \frac{(I_2 - I_1) \cdot T_S}{8 \cdot C} \quad V_{\text{RC}} = 1.204 \cdot \text{mV}$$

Find the ripple due to the ESR

$$V_{\text{RR}} := (I_2 - I_1) \cdot \text{ESR} \quad V_{\text{RR}} = 15.411 \cdot \text{mV}$$

Calculate the RMS ripple current for the capacitor.

Assume a triangular waveform with a 50% duty cycle - Worst case.

$$A := \frac{I_2 - I_1}{2} \quad A = 0.318 \cdot \text{amp}$$

$$I(t) := \frac{A}{\left(\frac{T_S}{4}\right)} \cdot t$$

$$I_{\text{rms}} := \sqrt{\frac{4}{T_S} \left[\int_{0 \cdot \text{sec}}^{\frac{T_S}{4}} I(t)^2 dt \right]}$$

$$I_{\text{rms}} = 0.184 \cdot \text{amp}$$

Repeat the same calculation with a non 50% duty cycle

$$I_1(t) := -A + \frac{2 \cdot A}{t_{\text{on}}} \cdot t \quad I_2(t) := A - \frac{2 \cdot A}{(T_S - t_{\text{on}})} \cdot t$$

$$I_{\text{rms}} := \sqrt{\frac{1}{T_S} \left(\int_{0 \cdot \text{sec}}^{t_{\text{on}}} I_1(t)^2 dt + \int_0^{T_S - t_{\text{on}}} I_2(t)^2 dt \right)}$$

$$I_{\text{rms}} = 0.184 \text{ charge} \cdot \text{time}^{-1}$$

Summary

Inductor

$$L = 0.39 \cdot \text{mH} \quad \text{Peak Current Rating} \quad I_2 = \text{function} \cdot \text{amp} \quad \text{Avg Current Rating} \quad I_o = 3 \cdot \text{amp}$$

Capacitor

$$C = 3.3 \cdot 10^3 \cdot \mu\text{F} \quad \text{RMS Ripple Current Rating} \quad I_{\text{rms}} = 0.184 \cdot \text{amp}$$

Regulator Specs

$$\text{Maximim Current} \quad I_o = 3 \cdot \text{amp} \quad \text{Period} \quad T_S = 50 \cdot \mu\text{s} \quad \text{Switching Frequency} \quad F_S = 20 \cdot \text{kHz}$$

$$\text{Switch on time} \quad t_{\text{on}} = 14.583 \cdot \mu\text{s} \quad \text{Output Voltage} \quad V_o = 7 \cdot \text{volt} \quad \text{Input Voltage} \quad V_D = 24 \cdot \text{volt}$$

$$\text{Currents} \quad I_2 = \text{function} \cdot \text{amp} \quad I_1 = \text{function} \cdot \text{amp} \quad I_2 - I_1 = \text{mA}$$

EE 456

Buck Regulator Design - Continuous Mode Operation

Design with minimum input voltage

Define useful units for Electrical Engineering

$$\mu\text{s} \equiv 10^{-6} \cdot \text{sec}$$

Specify Input Voltage $V_D := 12 \cdot \text{volt}$

Specify Output Voltage $V_o := 7 \cdot \text{volt}$

Specify Switching Frequency $F_S := 20 \cdot \text{kHz}$

$$T_S := \frac{1}{F_S}$$

$$T_S = 50 \cdot \mu\text{s}$$

Find on time assuming continuous mode operation. $t_{\text{on}} := \frac{V_o}{V_D} \cdot T_S$ $t_{\text{on}} = 29.167 \cdot \mu\text{s}$

Specify the Max output Current $I_o := 3 \cdot \text{amp}$

Design the buck regulator so that it operates in the continuous mode for currents down to 10% of the max current.

$$I_{o_min} := 0.1 \cdot I_o$$

$$I_{o_min} = 0.3 \cdot \text{amp}$$

Find L so that the buck regulator operates in continuous mode for the min output current

$$L := \frac{V_D - V_o}{2 \cdot I_{o_min}} \cdot t_{\text{on}}$$

$$L = 243.056 \cdot \mu\text{H}$$

Choose the next size std. inductor $L := 390 \cdot \mu\text{H}$

With chosen inductor, find min current for continuous operation

$$I_{o_min} := \frac{V_D - V_o}{2 \cdot L} \cdot t_{\text{on}}$$

$$I_{o_min} = 186.966 \cdot \text{mA}$$

For the Max output current, find I1 and I2

$$I_1 := I_o \quad I_2 := I_o$$

Given

$$\frac{I_2 + I_1}{2} = I_o$$

$$I_2 - I_1 = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} := \text{Find}(I_1, I_2) \quad I_2 = 3.187 \cdot \text{amp} \quad I_1 = 2.813 \cdot \text{amp}$$

$$I_2 - I_1 = 373.932 \cdot \text{mA}$$

For the Min output current, find I1 and I2

$$I_{1_} := I_{o_min} \quad I_{2_} := I_{o_min}$$

Given

$$\frac{I_{2_} + I_{1_}}{2} = I_{o_min}$$

$$I_{2_} - I_{1_} = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_{1_} \\ I_{2_} \end{bmatrix} := \text{Find}(I_{1_}, I_{2_}) \quad I_{2_} = 0.374 \cdot \text{amp} \quad I_{1_} = 0 \cdot \text{amp}$$

$$I_{2_} - I_{1_} = 373.932 \cdot \text{mA}$$

Choose the filter capacitor.

Assume that the major component of the ripple comes from the capacitor ESR

Specify the ripple due to the ESR $V_{RR} := 20 \cdot \text{mV}$

$$\text{ESR} := \frac{V_{RR}}{(I_2 - I_1)} \quad \text{ESR} = 0.053 \cdot \Omega$$

For all electrolytic caps, assume that $\text{ESR} \cdot C = 80 \mu\text{s}$

$$C := \frac{80 \cdot \mu\text{s}}{\text{ESR}} \quad C = 1495.7265 \cdot \mu\text{F}$$

Choose the next size std capacitor $C := 3300 \cdot \mu\text{F}$

Calculate the new ESR with the chosen capacitor

$$\text{ESR} := \frac{80 \cdot \mu\text{s}}{C} \quad \text{ESR} = 0.024 \cdot \Omega$$

Find the ripple due to the capacitor:

$$V_{\text{RC}} := \frac{(I_2 - I_1) \cdot T_S}{8 \cdot C} \quad V_{\text{RC}} = 0.708 \cdot \text{mV}$$

Find the ripple due to the ESR

$$V_{\text{RR}} := (I_2 - I_1) \cdot \text{ESR} \quad V_{\text{RR}} = 9.065 \cdot \text{mV}$$

Calculate the RMS ripple current for the capacitor.

Assume a triangular waveform with a 50% duty cycle - Worst case.

$$A := \frac{I_2 - I_1}{2} \quad A = 0.187 \cdot \text{amp}$$

$$I(t) := \frac{A}{\left(\frac{T_S}{4}\right)} \cdot t$$

$$I_{\text{rms}} := \sqrt{\frac{4}{T_S} \left[\int_{0 \cdot \text{sec}}^{\frac{T_S}{4}} I(t)^2 dt \right]}$$

$$I_{\text{rms}} = 0.108 \cdot \text{amp}$$

Summary

Inductor

$L = 0.39 \cdot \text{mH}$ Peak Current Rating $I_2 = 3.187 \cdot \text{amp}$ Avg Current Rating $I_o = 3 \cdot \text{amp}$

Capacitor

$C = 3.3 \cdot 10^3 \cdot \mu\text{F}$ RMS Ripple Current Rating $I_{\text{rms}} = 0.108 \cdot \text{amp}$

Regulator Specs

Maximim Current $I_o = 3 \cdot \text{amp}$ Period $T_S = 50 \cdot \mu\text{s}$ Switching Frequency $F_S = 20 \cdot \text{kHz}$

Switch on time $t_{\text{on}} = 29.167 \cdot \mu\text{s}$ Output Voltage $V_o = 7 \cdot \text{volt}$ Input Voltage $V_D = 12 \cdot \text{volt}$

Currents $I_2 = 3.187 \cdot \text{amp}$ $I_1 = 2.813 \cdot \text{amp}$ $I_2 - I_1 = 373.932 \cdot \text{mA}$

EE 456

Buck Regulator Design - Continuous Mode Operation

Design with maximum input voltage

Define useful units for Electrical Engineering

$$\mu\text{s} \equiv 10^{-6} \cdot \text{sec}$$

Specify Input Voltage $V_D := 24 \cdot \text{volt}$

Specify Output Voltage $V_o := 7 \cdot \text{volt}$

Specify Switching Frequency $F_S := 20 \cdot \text{kHz}$

$$T_S := \frac{1}{F_S} \quad T_S = 50 \cdot \mu\text{s}$$

Find on time assuming continuous mode operation. $t_{\text{on}} := \frac{V_o}{V_D} \cdot T_S$ $t_{\text{on}} = 14.583 \cdot \mu\text{s}$

Specify the Max output Current $I_o := 3 \cdot \text{amp}$

Design the buck regulator so that it operates in the continuous mode for currents down to 10% of the max current.

$$I_{o_min} := 0.1 \cdot I_o \quad I_{o_min} = 0.3 \cdot \text{amp}$$

Find L so that the buck regulator operates in continuous mode for the min output current

$$L := \frac{V_D - V_o}{2 \cdot I_{o_min}} \cdot t_{\text{on}} \quad L = 413.194 \cdot \mu\text{H}$$

Choose the next size std. inductor $L := 390 \cdot \mu\text{H}$

With chosen inductor, find min current for continuous operation

$$I_{o_min} := \frac{V_D - V_o}{2 \cdot L} \cdot t_{\text{on}} \quad I_{o_min} = 317.842 \cdot \text{mA}$$

For the Max output current, find I1 and I2

$$I_1 := I_o \quad I_2 := I_o$$

Given

$$\frac{I_2 + I_1}{2} = I_o$$

$$I_2 - I_1 = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} := \text{Find}(I_1, I_2) \quad I_2 = 3.318 \cdot \text{amp} \quad I_1 = 2.682 \cdot \text{amp}$$

$$I_2 - I_1 = 635.684 \cdot \text{mA}$$

For the Min output current, find I1 and I2

$$I_{1_} := I_{o_min} \quad I_{2_} := I_{o_min}$$

Given

$$\frac{I_{2_} + I_{1_}}{2} = I_{o_min}$$

$$I_{2_} - I_{1_} = \frac{V_D - V_o}{L} \cdot t_{on}$$

$$\begin{bmatrix} I_{1_} \\ I_{2_} \end{bmatrix} := \text{Find}(I_{1_}, I_{2_}) \quad I_{2_} = 0.636 \cdot \text{amp} \quad I_{1_} = 0 \cdot \text{amp}$$

$$I_{2_} - I_{1_} = 635.684 \cdot \text{mA}$$

Choose the filter capacitor.

Assume that the major component of the ripple comes from the capacitor ESR

Specify the ripple due to the ESR $V_{RR} := 20 \cdot \text{mV}$

$$\text{ESR} := \frac{V_{RR}}{(I_2 - I_1)} \quad \text{ESR} = 0.031 \cdot \Omega$$

For all electrolytic caps, assume that $\text{ESR} \cdot C = 80 \mu\text{s}$

$$C := \frac{80 \cdot \mu\text{s}}{\text{ESR}} \quad C = 2542.735 \cdot \mu\text{F}$$

Choose the next size std capacitor $C := 3300 \cdot \mu\text{F}$

Calculate the new ESR with the chosen capacitor

$$\text{ESR} := \frac{80 \cdot \mu\text{s}}{C} \quad \text{ESR} = 0.024 \cdot \Omega$$

Find the ripple due to the capacitor:

$$V_{\text{RC}} := \frac{(I_2 - I_1) \cdot T_S}{8 \cdot C} \quad V_{\text{RC}} = 1.204 \cdot \text{mV}$$

Find the ripple due to the ESR

$$V_{\text{RR}} := (I_2 - I_1) \cdot \text{ESR} \quad V_{\text{RR}} = 15.411 \cdot \text{mV}$$

Calculate the RMS ripple current for the capacitor.

Assume a triangular waveform with a 50% duty cycle - Worst case.

$$A := \frac{I_2 - I_1}{2} \quad A = 0.318 \cdot \text{amp}$$

$$I(t) := \frac{A}{\left(\frac{T_S}{4}\right)} \cdot t$$

$$I_{\text{rms}} := \sqrt{\frac{4}{T_S} \left[\int_{0 \cdot \text{sec}}^{\frac{T_S}{4}} I(t)^2 dt \right]}$$

$$I_{\text{rms}} = 0.184 \cdot \text{amp}$$

Summary

Inductor

$L = 0.39 \cdot \text{mH}$ Peak Current Rating $I_2 = 3.318 \cdot \text{amp}$ Avg Current Rating $I_o = 3 \cdot \text{amp}$

Capacitor

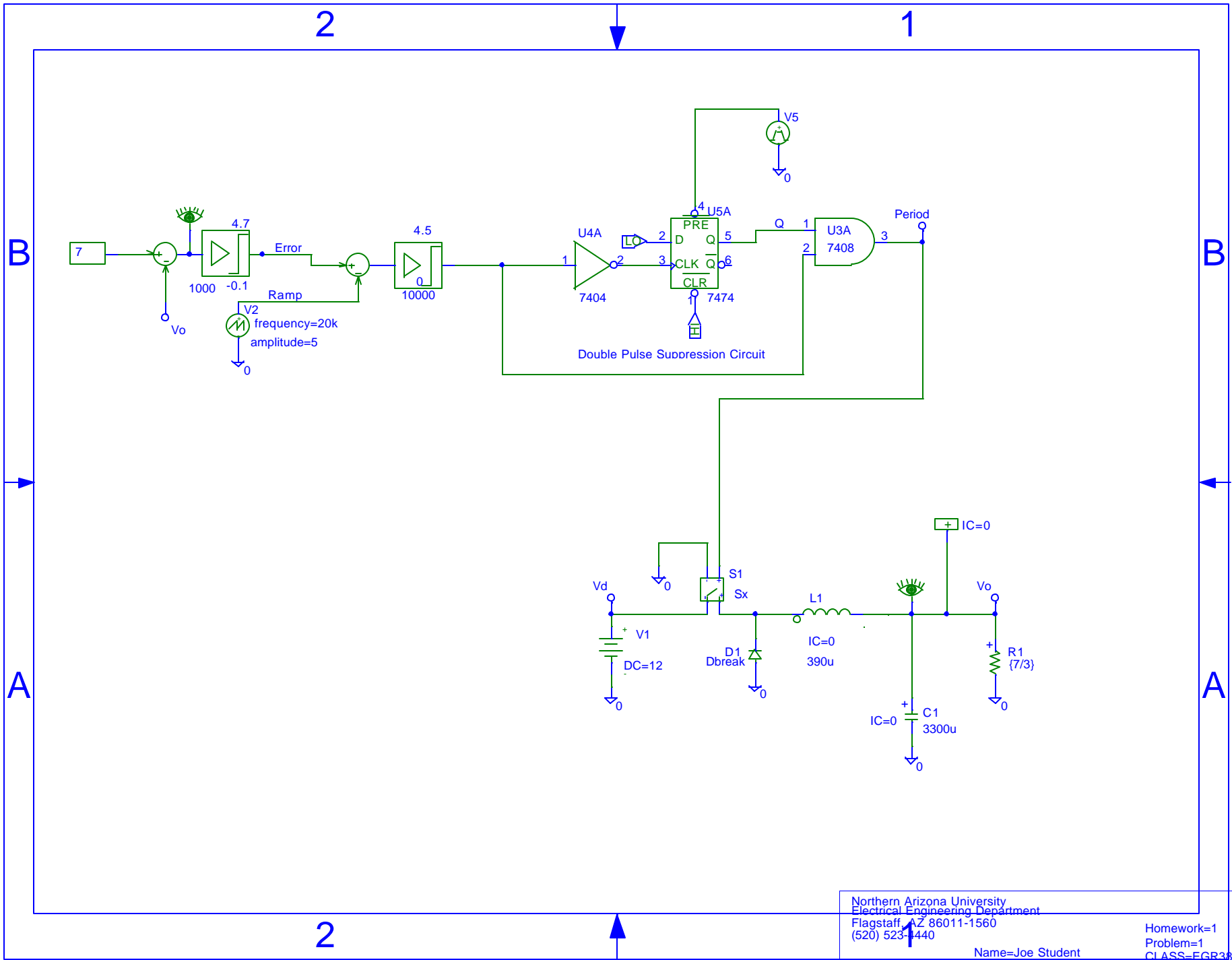
$C = 3.3 \cdot 10^3 \cdot \mu\text{F}$ RMS Ripple Current Rating $I_{\text{rms}} = 0.184 \cdot \text{amp}$

Regulator Specs

Maximim Current $I_o = 3 \cdot \text{amp}$ Period $T_S = 50 \cdot \mu\text{s}$ Switching Frequency $F_S = 20 \cdot \text{kHz}$

Switch on time $t_{\text{on}} = 14.583 \cdot \mu\text{s}$ Output Voltage $V_o = 7 \cdot \text{volt}$ Input Voltage $V_D = 24 \cdot \text{volt}$

Currents $I_2 = 3.318 \cdot \text{amp}$ $I_1 = 2.682 \cdot \text{amp}$ $I_2 - I_1 = 635.684 \cdot \text{mA}$

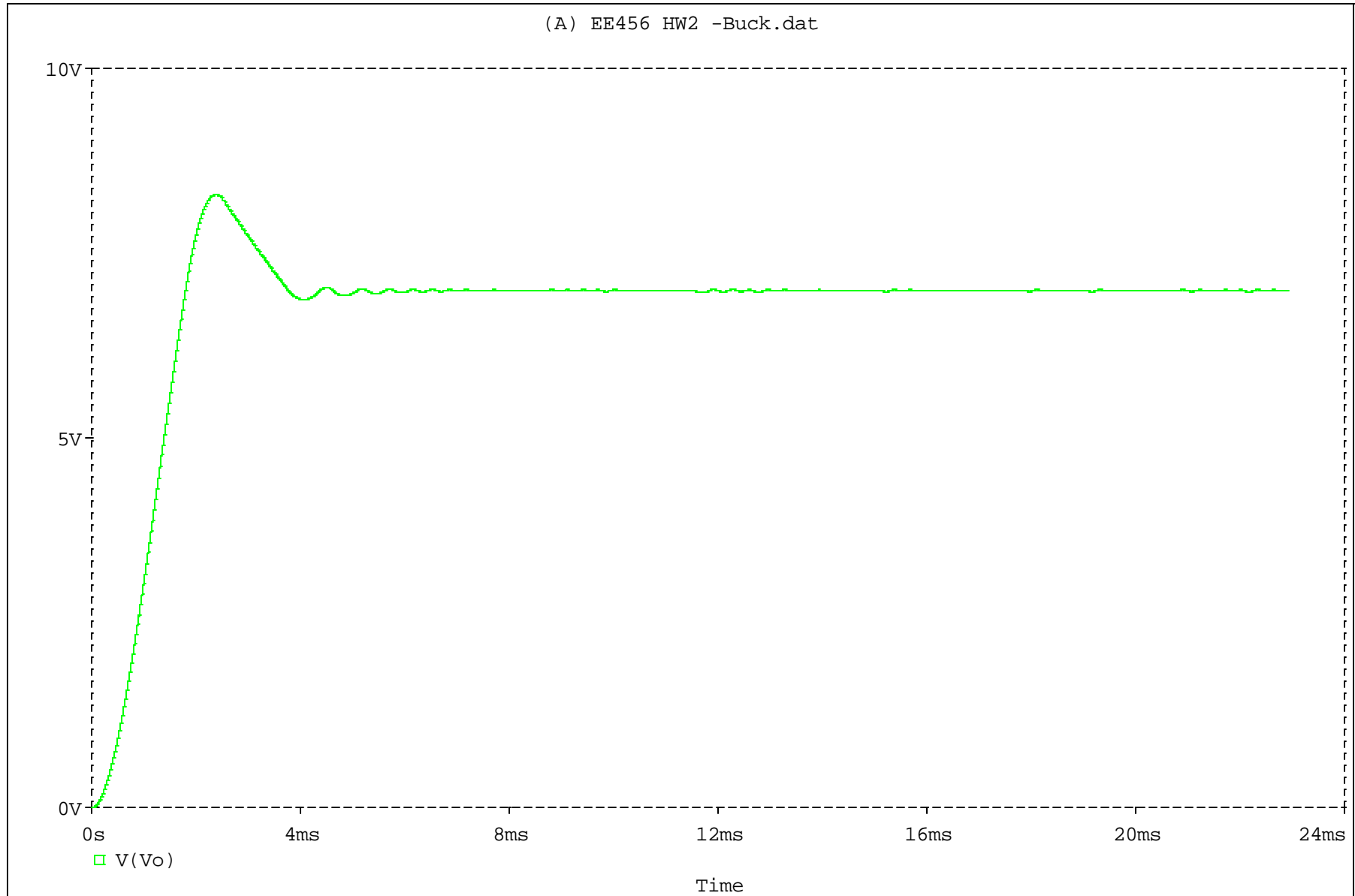


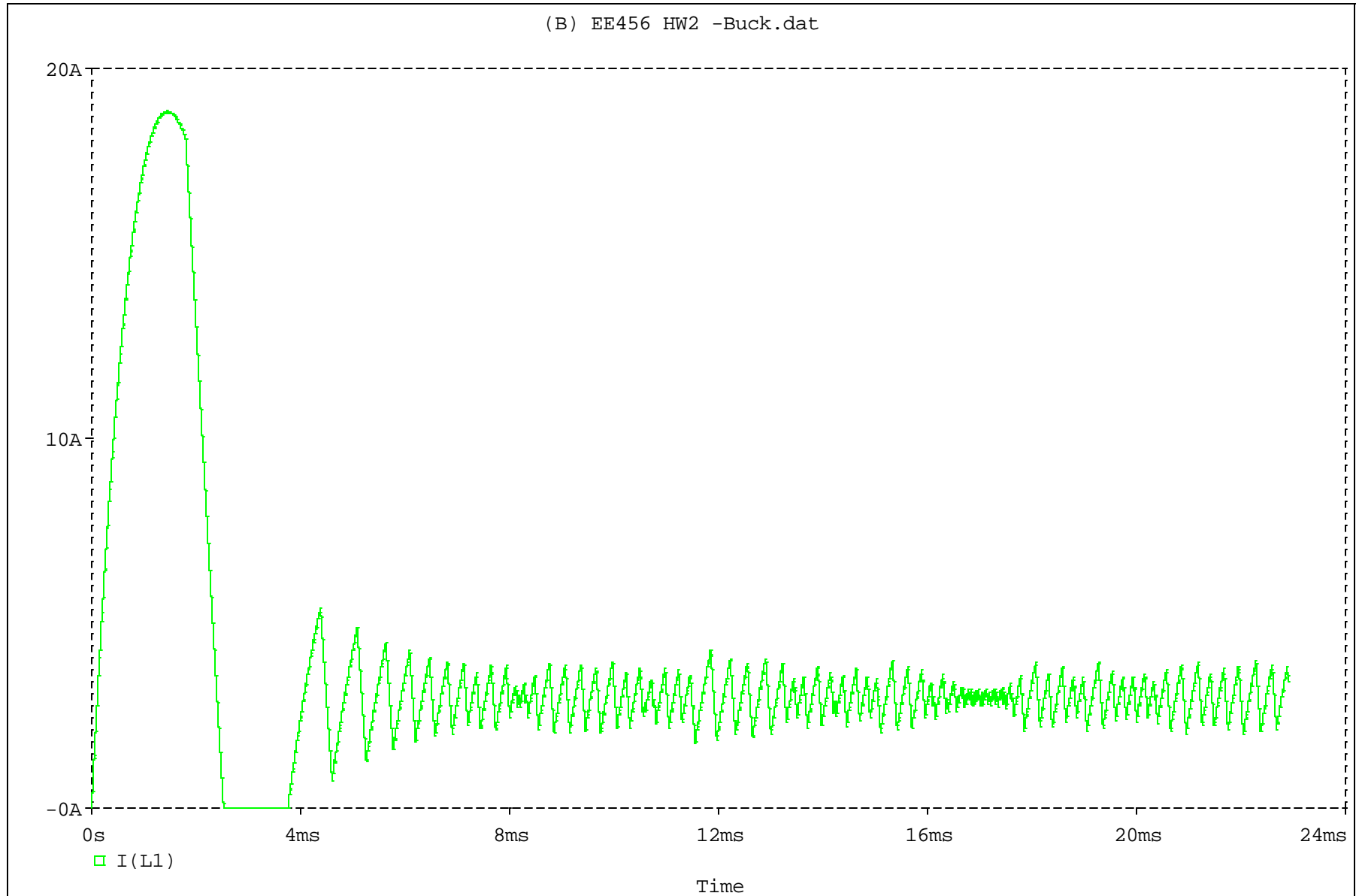
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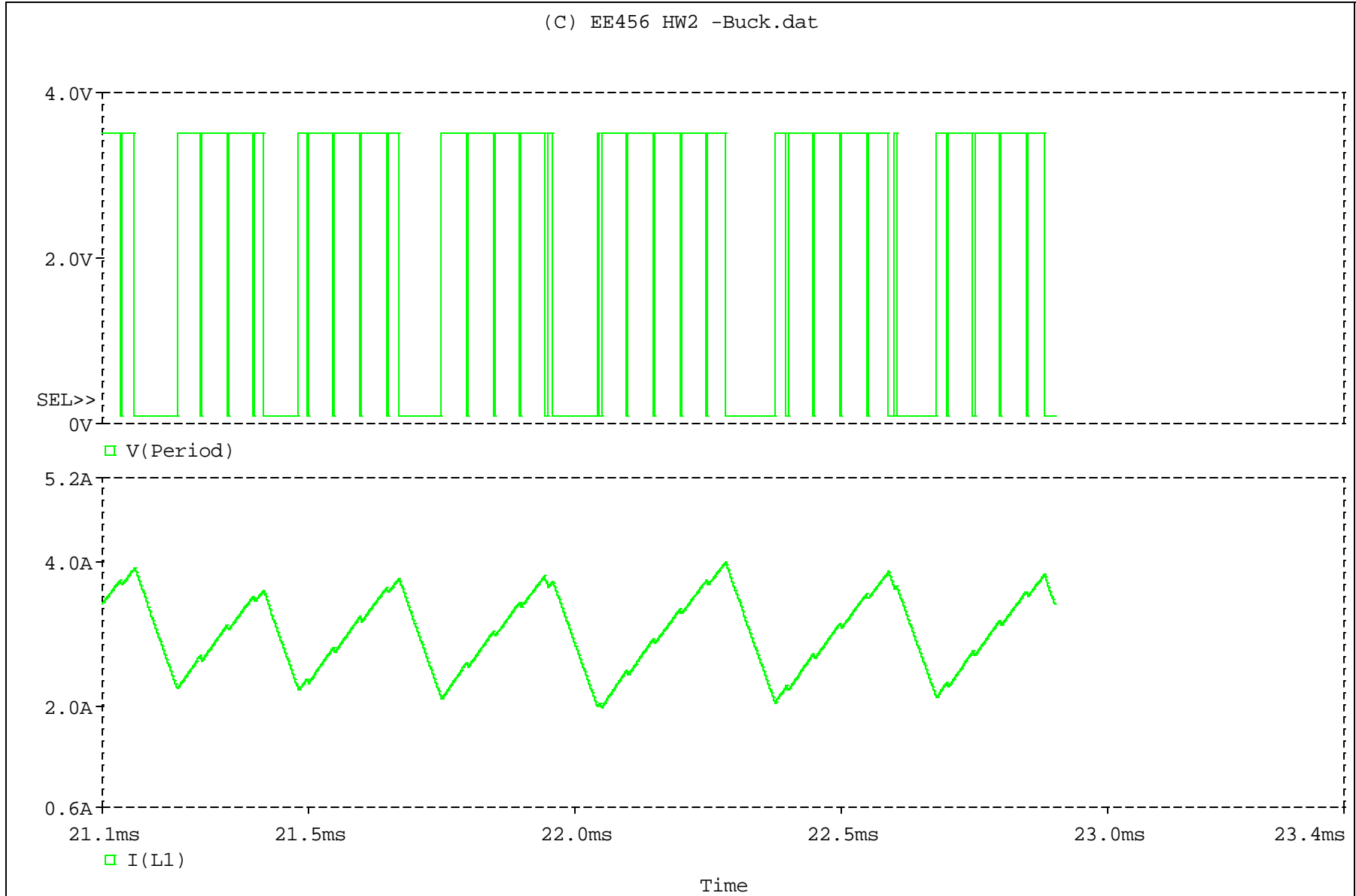
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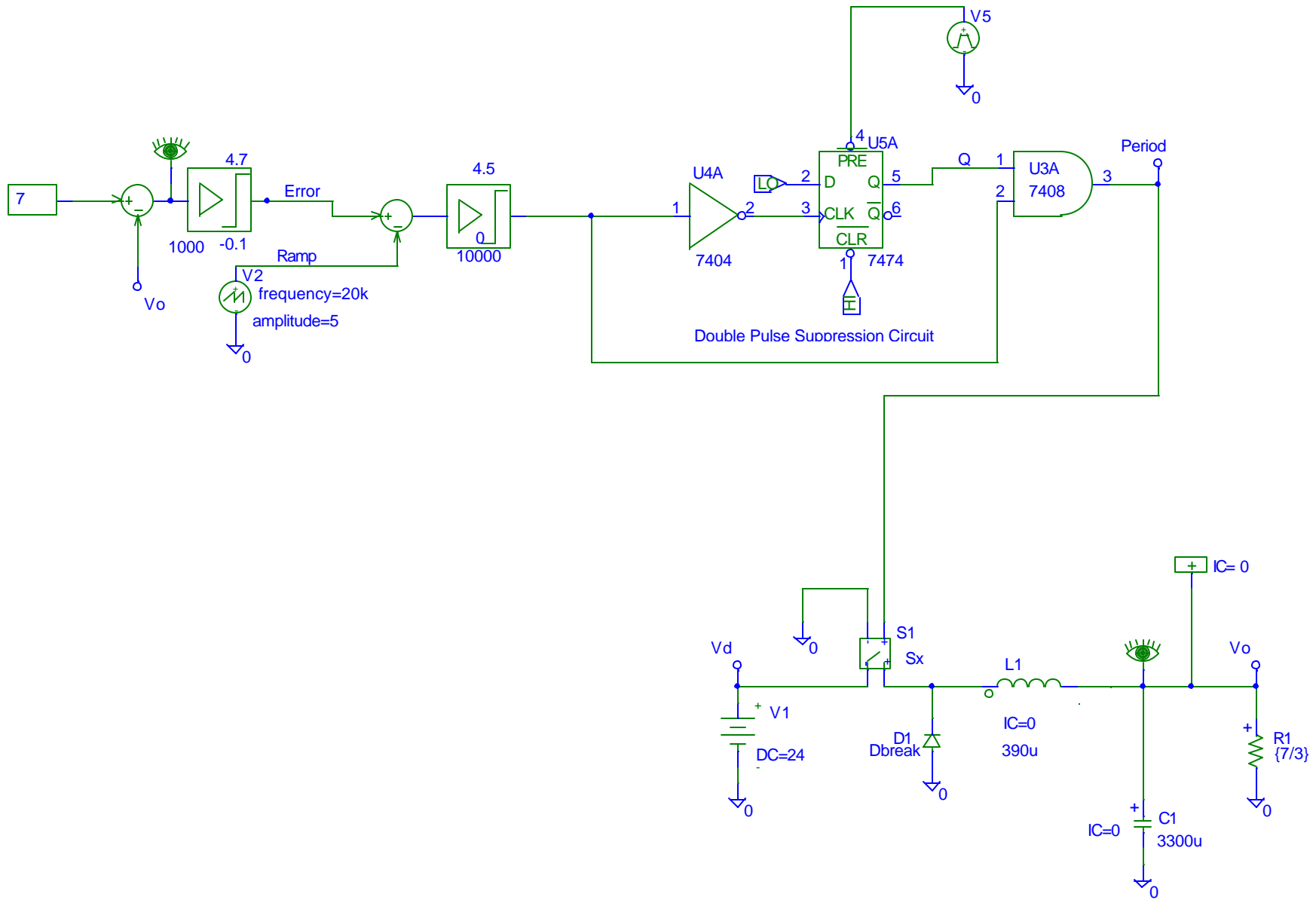
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 Semester=Fall 92
 Prof.=Herniter
 January 1, 2000

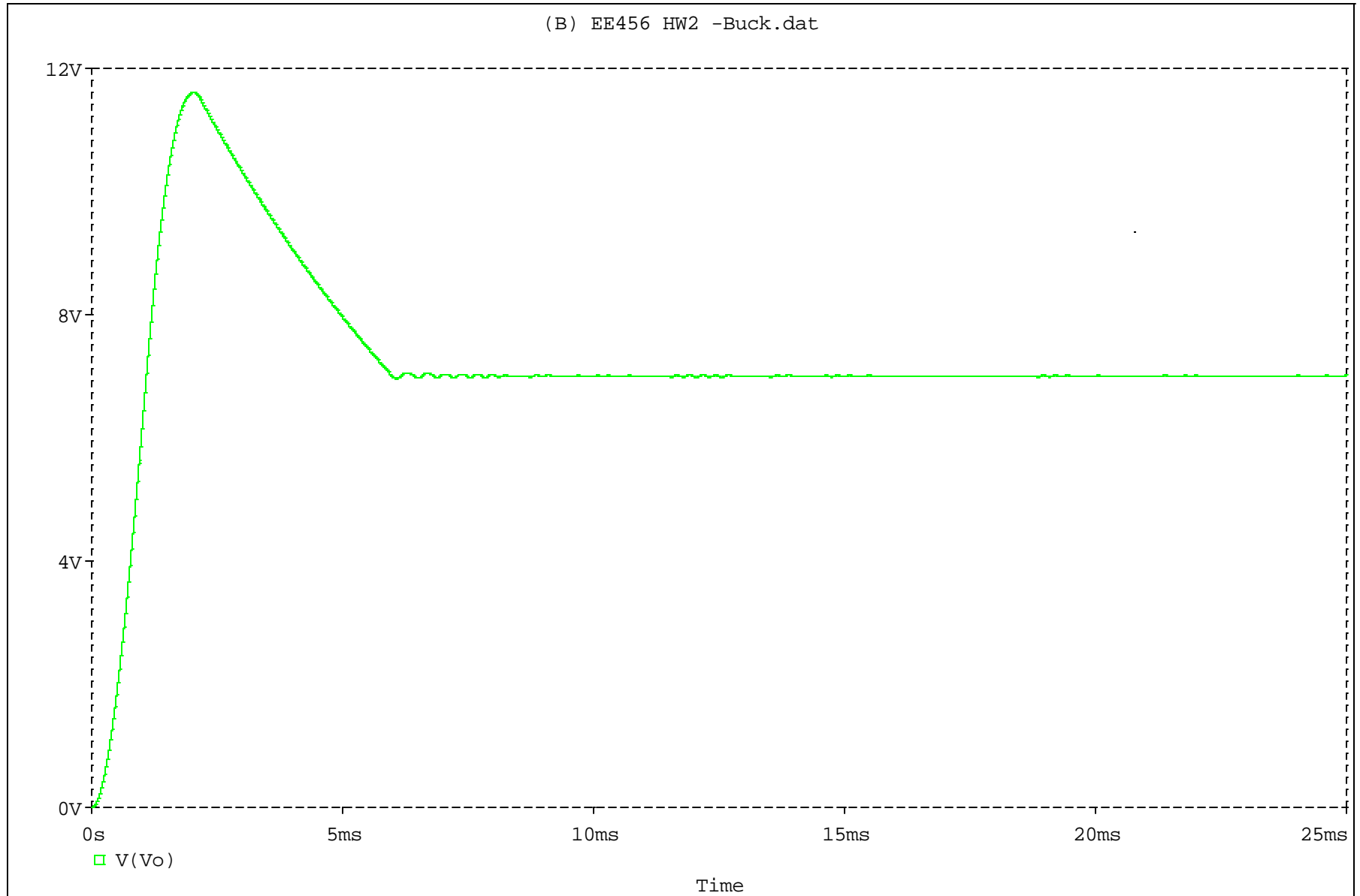
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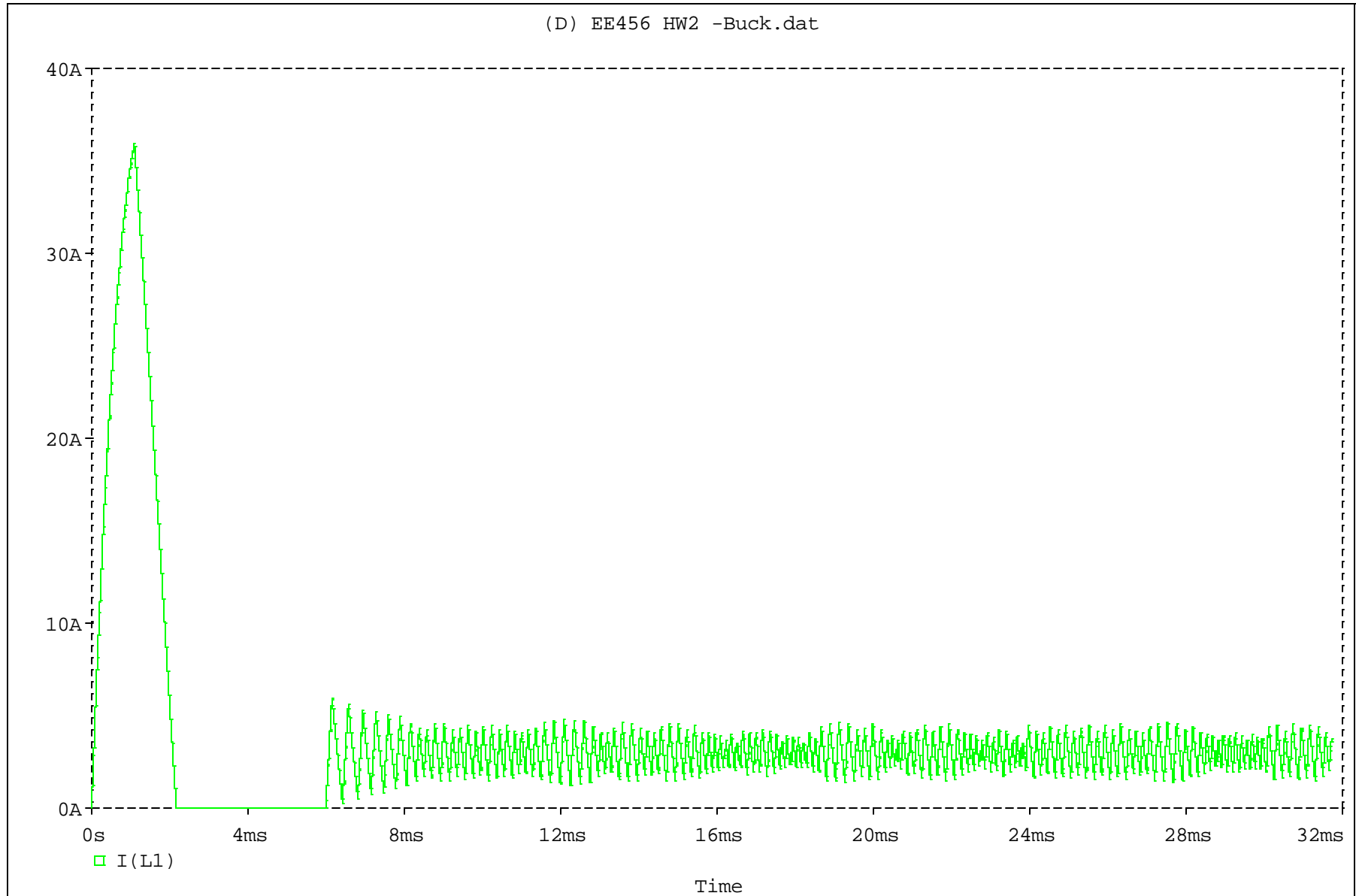


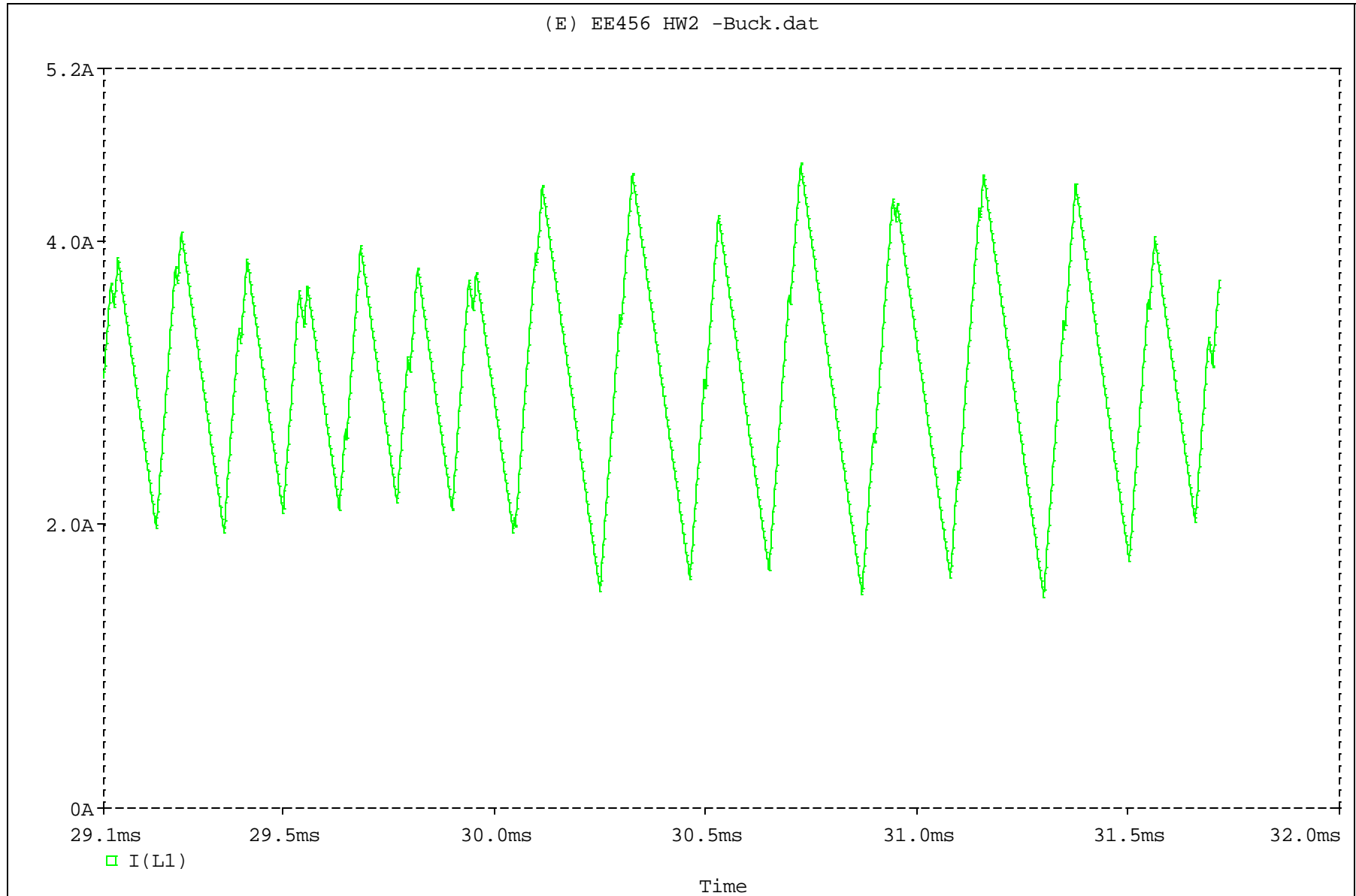


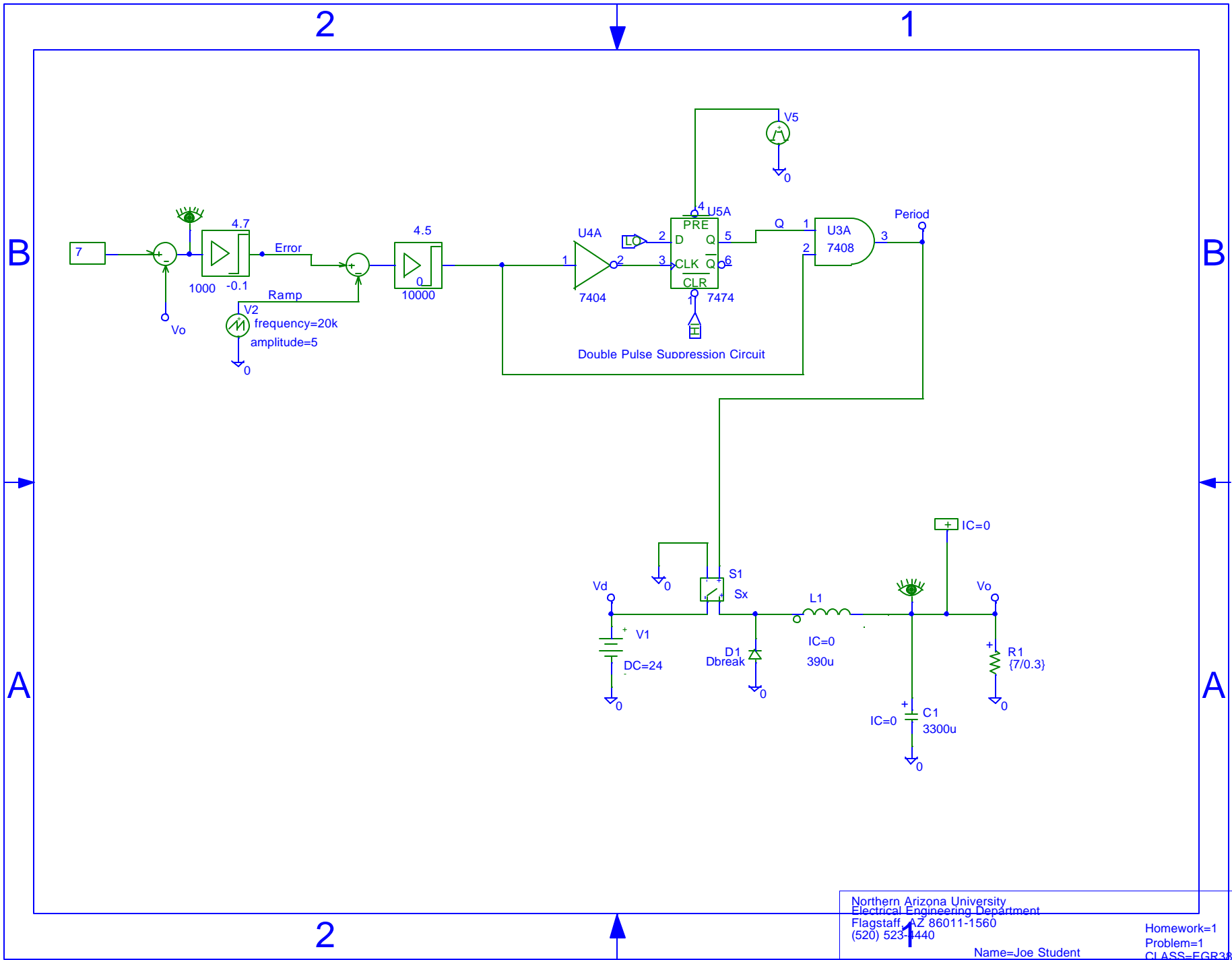












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